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Preliminary Investigations of Hydric Soil Hydrology and Morphology in the United States

Edited by James S. Wakeley, Steven W. Sprecher, Warren C. Lynn

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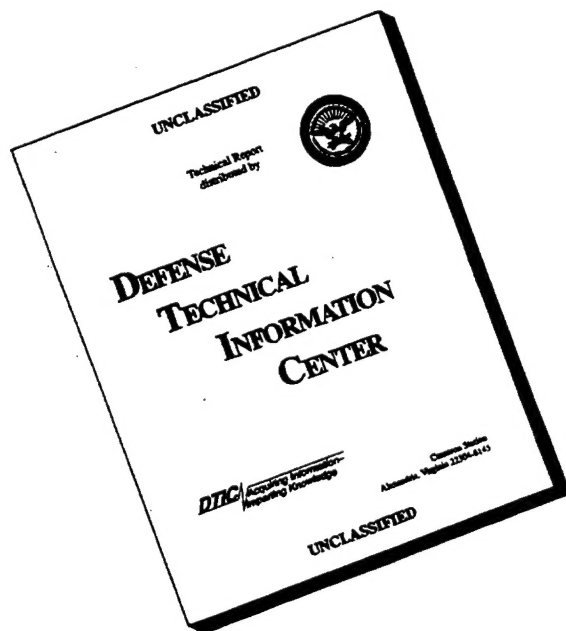


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CP	Critical Processes	RE	Restoration & Establishment
DE	Delineation & Evaluation	SM	Stewardship & Management

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Preliminary Investigations of Hydric Soil Hydrology and Morphology in the United States

Edited by James S. Wakeley, Steven W. Sprecher

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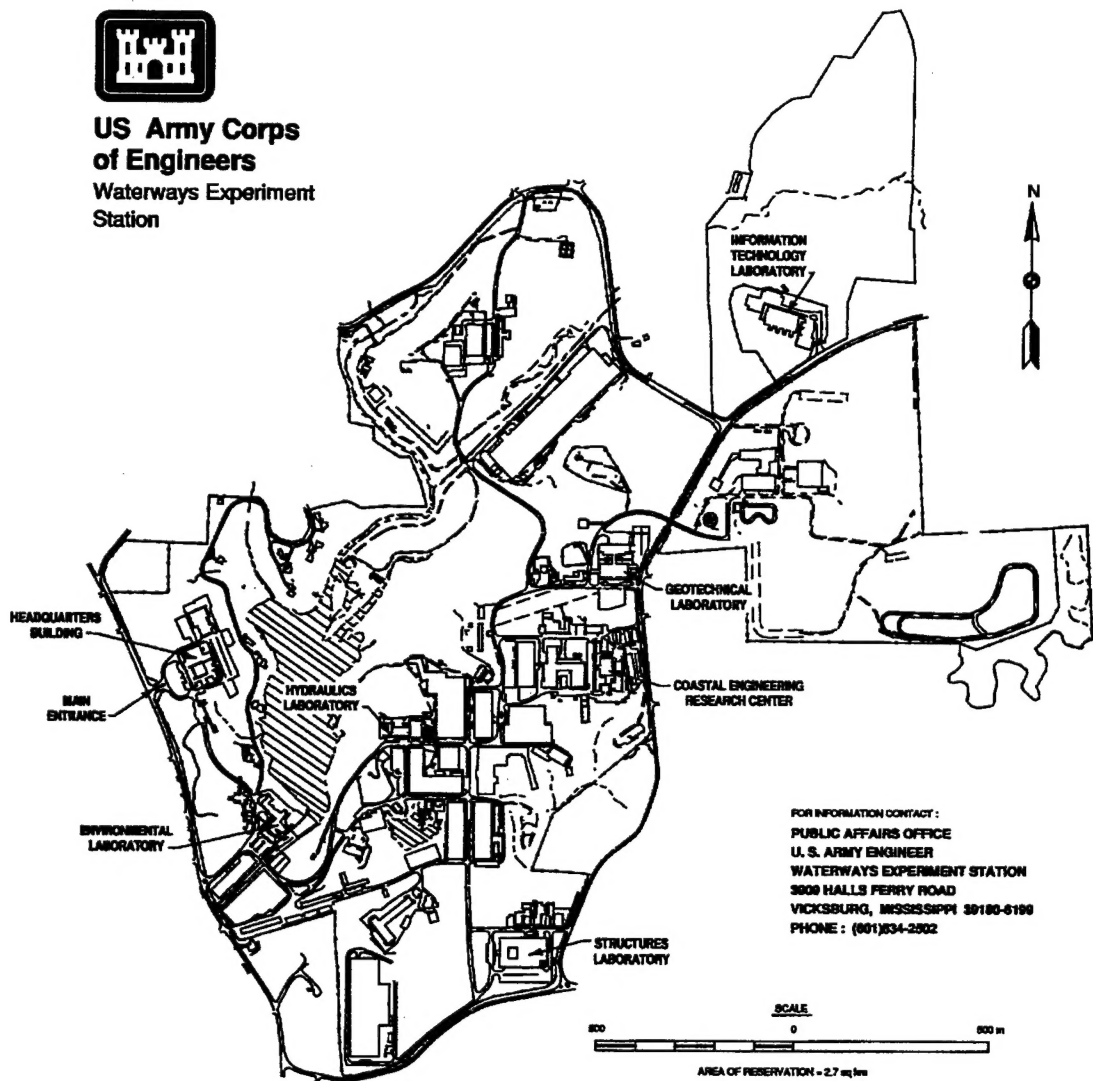
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Hydric Soils Investigations

Preliminary Investigations of Hydric Soil Hydrology and Morphology in the United States (TR WRP-DE-13)

ISSUE:

The definition and recognition of hydric soils are central to methods of wetland delineation. Long-term studies in eight States seek to understand the complex relationships among soil hydrology, temperature, oxidation/reduction status, and the development of hydric soil morphology.

RESEARCH:

Investigators at land-grant universities are using similar instruments and research designs to investigate seasonal timing of and time lags between onset of saturation, anaerobiosis, and iron reduction at various depths; effects of soil temperature and relationships to growing season; and morphological features that identify soils meeting hydric soil criteria.

SUMMARY:

Preliminary results based on 2 years of monitoring at most sites indicate that time lags between

saturation and iron reduction range from several days to several weeks, depending upon temperature and other factors. Growing seasons based on measured soil temperatures often differed considerably from approximations based on air temperatures and soil temperature regime regions. Due to annual variability, longer monitoring periods are needed to identify reliable hydric soil indicators.

AVAILABILITY OF REPORT:

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About the Authors:

This report was written mainly by university researchers in eight states—Alaska, Indiana, Louisiana, Minnesota, New Hampshire, North Dakota, Oregon, and Texas—in cooperation with the U.S. Department of Agriculture Natural Resources Conservation Service (NRCS). The report was edited by Drs. James S. Wakely, Research Wildlife Biologist, and Steven W. Sprecher, Soil Scientist, at the WES Environmental Laboratory and Dr. Warren C. Lynn of the NRCS. Point of contact is Dr. Wakeley at (601) 634-3702.

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Preface

The work described in this report was authorized by Headquarters, U.S. Army Corps of Engineers (HQUSACE), as part of the Wetland Delineation and Evaluation Task Area of the Wetlands Research Program (WRP). The work was performed under Work Unit 32755, "Wetland Delineation," for which Dr. James S. Wakeley was Technical Manager. Mr. Sam Collinson (CECW-OR) was the WRP Technical Monitor for this work.

Mr. Dave Mathis (CERD-C) was the WRP Coordinator at the Directorate of Research and Development, HQUSACE; Dr. William L. Klesch (CECW-PO) served as the WRP Technical Monitor's Representative; Dr. Russell F. Theriot, Environmental Laboratory (EL), U.S. Army Engineer Waterways Experiment Station (WES), was the Wetlands Program Manager. Mr. Ellis J. Clairain, Jr., EL, was the Task Area Manager.

The work was performed by investigators associated with the University of Alaska, Louisiana State University, University of Minnesota, University of New Hampshire, North Dakota State University, Oregon State University, Purdue University, and Texas A&M University in cooperation with the U.S. Department of Agriculture Natural Resources Conservation Service (NRCS) and WES. Editors of this report were Drs. Wakeley and Steven W. Sprecher, Wetlands Branch (WB), Ecological Research Division (ERD), EL, and Dr. Warren C. Lynn, NRCS. This report was prepared under the direct supervision of Mr. E. Carl Brown, Chief, WB; Dr. Conrad J. Kirby, Chief, ERD; and Dr. John W. Keeley, Director, EL.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Bruce K. Howard, EN.

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Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
Fahrenheit degrees	5/9	Celsius degrees or kelvins ¹
feet	0.3048	meters
inches	2.54	centimeters

¹ To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9) (F - 32)$. To obtain kelvin (K) readings, use the following formula: $K = (5/9) (F - 32) + 273.15$.

1 Background of the Wet Soils Monitoring Project¹

Project Purposes

The Wet Soils Monitoring Project is a coordinated effort among investigators at Land Grant Universities in eight States (Figure 1). These long-term studies were initiated and supported by the U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS, formerly the Soil Conservation Service) National Soil Survey Center as part of the Global Change Initiative, with additional funds provided by the U.S. Army Corps of Engineers (CE) Wetlands Research Program through the U.S. Army Engineer Waterways Experiment Station.

The studies have been designed to address several different objectives simultaneously. Under the Global Change Initiative, NRCS is interested in understanding the dynamics of soil hydrology, soil moisture, and oxidation/reduction processes in various landscapes and regions, and in collecting baseline soil property data as a reference for assessing climatic changes in future years. In addition, the studies will generate information needed to answer questions about the classification of wet soils in *Soil Taxonomy* (Soil Survey Staff 1975, 1994). The CE's interests in the project stem from the agency's regulatory responsibilities in wetlands under Section 404 of the Clean Water Act, and the need to refine methods used to identify and delineate wetland boundaries (Environmental Laboratory 1987). Results of the monitoring studies will provide valuable insights into the definition and field recognition of hydric soils.

One of the most valuable goals of the project is to establish and maintain a database of long-term soil monitoring data that can be accessed readily in the future when specific questions arise about the relationships among soil saturation, oxidation/reduction status, and development of soil morphological

¹ Written by Warren C. Lynn, USDA Natural Resources Conservation Service, National Soil Survey Center, Federal Building, Room 152, MS 41, 100 Centennial Mall North, Lincoln, NE 68508-3866; and Steven W. Sprecher and James S. Wakeley, U.S. Army Engineer Waterways Experiment Station, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199.

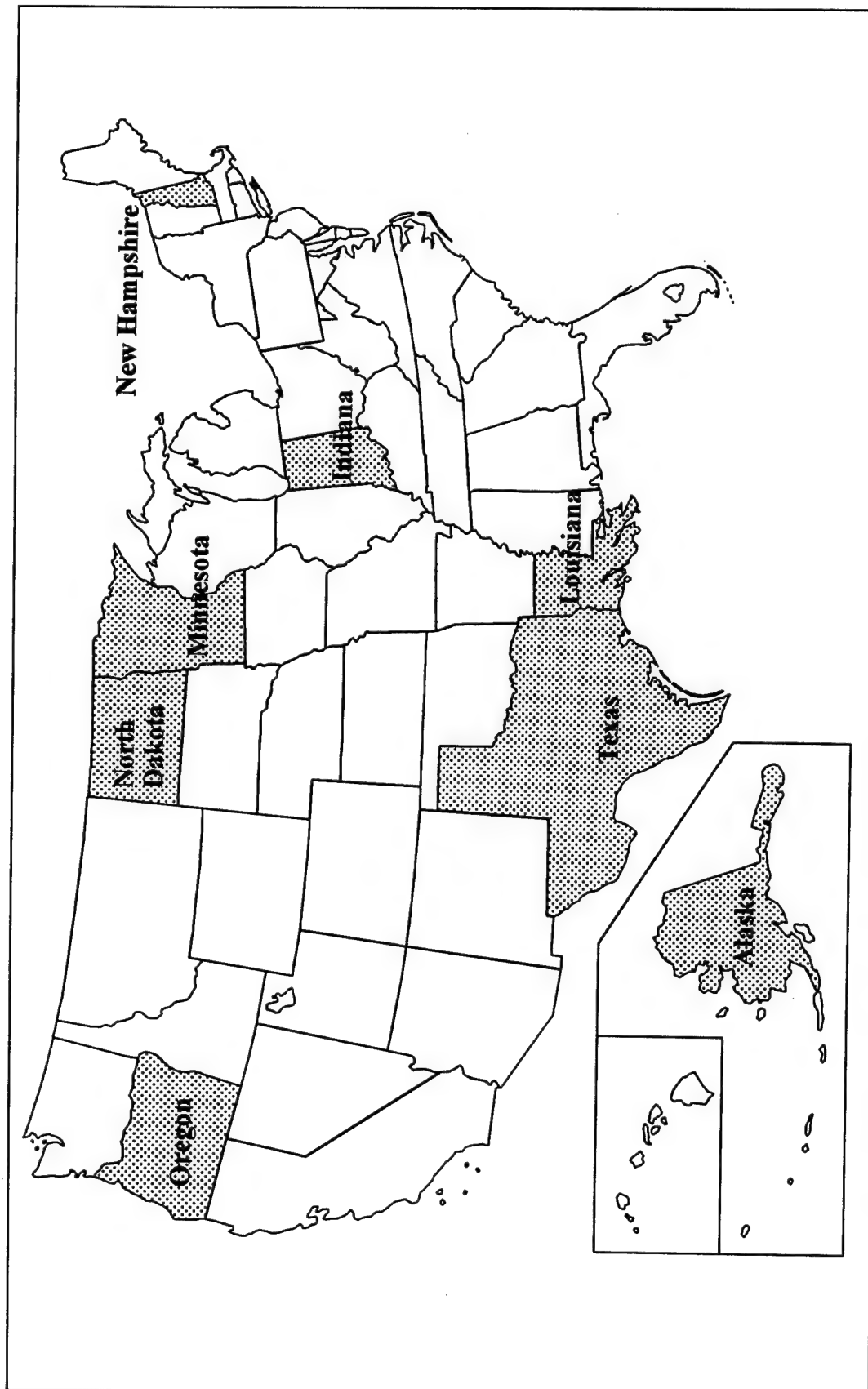


Figure 1. States participating in the Wet Soils Monitoring Project

characteristics. The database is being developed and will be maintained by the NRCS National Soil Survey Center in Lincoln, NE. Requests for information should be directed to Dr. Warren Lynn at the address given in the footnote.

Beginnings of the Project

Projects were initiated in Louisiana and Texas in 1988 for the purpose of providing study sites for the International Committee on Aquic Soil Moisture Regimes (ICOMAQ). ICOMAQ was one of several international committees established to work on designated topics related to *Soil Taxonomy*. The ICOMAQ studies were directed by Dr. Wayne Hudnall at Louisiana State University and Dr. Larry Wilding at Texas A&M University, in collaboration with NRCS soil scientists. In each State, the work involved detailed description, instrumentation, characterization, and analysis of a number of different soils. Depth, duration, and frequency of soil saturation were monitored at 2-week intervals with replicated piezometers and tensiometers installed to various depths in the profile. Reduction status was determined by measuring redox potentials at each depth every 2 weeks and by a chemical test for ferrous iron. Precipitation was monitored with rain gauges and soil temperatures with thermistors installed at two depths. The sites and accumulated data were inspected by ICOMAQ members in 1990, resulting in a better understanding of aquic soil moisture regimes and proposals for amendments to *Soil Taxonomy*.

The start of the Global Change Initiative and experience in Louisiana and Texas prompted NRCS to initiate additional projects in other major kinds of wet soil landscapes and climates. Four sites were established in 1991: (a) in Alaska under the direction of Dr. Chien-Lu Ping, (b) in Indiana with Dr. Donald Franzmeier, (c) in North Dakota with Dr. Jim Richardson, and (d) in Oregon with Dr. Herbert Huddleston. At about the same time, the CE initiated its Wetlands Research Program, which, among other objectives, sought to strengthen the technical foundations of the "Corps of Engineers Wetlands Delineation Manual" (Environmental Laboratory 1987) and refine methods for field recognition of hydric soils. At the invitation of NRCS, representatives of the U.S. Army Engineer Waterways Experiment Station (Drs. Steve Sprecher and Jim Wakeley) attended a coordination meeting for the new project leaders, discussed the relevance of the project to hydric soils issues, offered suggestions on research design to help address regulatory questions, and provided additional funds to each site to help defray start-up costs.

Two additional study sites were established by NRCS in 1992. The Minnesota study, under the direction of Dr. Jay Bell, focused on Mollisol landscapes and was given supplementary funding by the CE Wetlands Research Program. The New Hampshire study was a continuation of earlier investigations of water table fluctuations led by Steve Hundley, NRCS State Soil Scientist. The new work, conducted jointly by Steve Hundley and Dr. Christine

Evans at the University of New Hampshire, required the installation of an expanded array of sensors similar to those at other Wet Soils Monitoring sites.

Purpose of this Report

The purpose of this report is to present preliminary results of the Wet Soils Monitoring Project, with emphasis on findings relevant to the formation and recognition of hydric soils. These results are preliminary in that only 2 years of monitoring data had accumulated at most sites when the reports were written—too little time to draw firm conclusions about long-term average conditions or to quantify the inherent variability in water table and redox measurements. The NRCS hopes to maintain the monitoring program at these sites for at least 10 years. After that time, investigators will have a much better understanding of the relationships between hydrology and morphology of the monitored soils.

However, even in the short term, these studies provide valuable insights into water table dynamics, groundwater flow, and the seasonal timing of and time lags between soil saturation and reduction at sites throughout the United States. For preparation of this report, each research team was asked to address three issues important to hydric soil and wetland determinations: (a) what are the relationships among saturation, anaerobiosis, and reduction in the sampled soils, (b) how does soil temperature affect anaerobiosis and reduction in these soils, and (c) within the constraints of a short-term study, what morphological features might be useful in identifying soils that meet hydric soil criteria (USDA Soil Conservation Service 1991)?

Hydric Soils Background Information

Research data described in this report were interpreted in the context of hydric soils conventions current in 1993 and 1994. Wetland and hydric soils concepts change with time as new knowledge is gained. The following is a summary of hydric soils concepts that were current at the time this report was being written.

Hydric soils have traditionally been identified in the field on the basis of the hydric soils definition, hydric soils criteria, or hydric soils field indicators. Field indicators consist of soil morphological characteristics present in many hydric soils. Field indicators are most frequently used in wetland regulatory situations because they can be observed readily during a brief site visit. Use of the hydric soil definition has generally been limited to research situations, because it requires knowledge of transient periods of oxygen depletion in the soil. Application of hydric soils criteria requires long-term monitoring of water levels above or below the soil surface and, thus, is useful only when stream gauge or groundwater well data are available for a site.

Hydric soil definition and criteria

At the time these reports were written, the definition of a hydric soil was as follows: "A hydric soil is a soil that is saturated, flooded, or ponded long enough during the growing season to develop anaerobic conditions in the upper part" (USDA Soil Conservation Service 1991). Hydric soil criteria were as follows:¹

1. All Histosols except Folists, or
2. Soils in Aquic suborders, Aquic subgroups, Albolls suborder, Salorthids great group, Pell great groups of Vertisols, Pachic subgroups, or Cumulic subgroups that are:
 - a. Somewhat poorly drained and have a frequently occurring water table at less than 0.5 foot (ft) from the surface for a significant period (usually more than 2 weeks) during the growing season, or
 - b. Poorly drained or very poorly drained and have either:
 - (1) a frequently occurring water table at less than 0.5 ft from the surface for a significant period (usually more than 2 weeks) during the growing season if textures are coarse sand, sand, or fine sand in all layers within 20 inches (in), or for other soils
 - (2) a frequently occurring water table at less than 1.0 ft from the surface for a significant period (usually more than 2 weeks) during the growing season if permeability is equal to or greater than 6.0 in/hour (h) in all layers within 20 in, or
 - (3) a frequently occurring water table at less than 1.5 ft from the surface for a significant period (usually more than 2 weeks) during the growing season if permeability is less than 6.0 in/h in any layer within 20 in, or
3. Soils that are frequently ponded for long duration or very long duration during the growing season, or
4. Soils that are frequently flooded for long duration or very long duration during the growing season.

Information gathered as part of the Wet Soils Monitoring Project can help to refine both the hydric soils definition and criteria. Important issues include (a) duration of soil saturation needed to cause anaerobiosis and reduction of iron, (b) validity of the concept of a growing season defined on the basis of a

¹ A table of factors for converting non-SI units of measurement to SI units is presented on page viii.

5 °C temperature threshold for soil biological activity, (c) height above a water table at which saturation, anaerobiosis, or reduction may occur, and (d) regional variations in the relationships among soil hydrology, anaerobiosis, iron reduction, and development of soil morphological characteristics.

No consensus currently exists on how to apply the hydric soils criteria in the field. Many wetland regulators and environmental consultants argue for the presence or absence of hydric soils on the basis of the criteria and water table data. The National Technical Committee for Hydric Soils, however, has recently urged caution in interpreting water table data using the hydric soil criteria (Mausbach 1994), because the criteria were designed primarily to generate hydric soil lists from the NRCS database of Soils Interpretation Records and not for identification of hydric soils in the field.

Growing season

The definition and criteria for hydric soil are stated in terms of the growing season, on the assumption that the chemistry of soil reduction is biologically driven and therefore is insignificant when soil temperature is below 5 °C (termed biological zero). Because wetland scientists seldom monitor soil temperatures, various estimates of the growing season have been recommended. Some of the papers in this report evaluate these recommendations.

The growing season is defined as "the portion of the year when soil temperatures are above biologic zero in the upper part" (USDA Soil Conservation Service 1991). The depth of "the upper part" of the soil has not been defined. *Soil Taxonomy* (Soil Survey Staff 1994) uses temperatures at 50 cm (20 in.) to define soil temperature regimes. The CE (Environmental Laboratory 1987) considers the critical interval to be the "... major portion of the root zone (usually within 12 inches (30 cm) of the surface)..." The National Technical Committee for Hydric Soils recommended growing seasons based on soil temperature regimes according to the following schedule of inclusive dates (USDA Soil Conservation Service 1991):

Isohyperthermic:	January-December
Hyperthermic:	February-December
Isothermic:	January-December
Thermic:	February-October
Isomesic:	January-December
Mesic:	March-October
Frigid:	May-September
Cryic:	June-August
Pergelic:	July-August

However, this system for estimating growing season length is impractical for regulatory purposes because it results in sudden discontinuities at regional boundaries.

In March 1992, the CE provided guidance to its personnel that the growing season could be estimated from climatological tables in local county soil survey reports as the period between last and first occurrences of 28 °F air temperatures at a frequency of 5 years in 10. The NRCS uses the same rule in the third edition of its *National Food Security Act Manual* (USDA Soil Conservation Service 1994).

Hydric soil indicators

Wetland scientists usually identify hydric soils in the field by interpreting soil morphology. Lists of soil morphologies, called field indicators, have been developed to assist people who need to identify hydric soils but are not professional soil scientists. Presence of any of the listed indicators is sufficient to identify the soil as hydric for purposes of Federal jurisdictional wetland delineation. The most commonly used list is found in the "Corps of Engineers Wetlands Delineation Manual" (Environmental Laboratory 1987).

Since 1993, the NRCS has been developing regionalized lists of hydric soil field indicators. The 1 February 1994 draft version was provided to investigators of the Wet Soils Monitoring Project. Some investigators refer to indicators from one or the other of these lists. Field indicators recommended by the Environmental Laboratory (1987) are listed in Table 1. Draft NRCS indicators discussed in individual project reports are quoted in the reports.

Table 1 Field Indicators of Hydric Soils (Environmental Laboratory 1987)	
Nonsandy Soils	1. Organic soils (Histosols)
	2. Histic epipedon
	3. Sulfidic material
	4. Aquic or peraquic moisture regime
	5. Reducing soil conditions
	6. Soil color (matrix chroma of 2 or less with mottles, or 1 or less with or without mottles, immediately below the A horizon or within 10 in.)
	7. Soil appears on the hydric soils list
	8. Fe and Mn concretions
Sandy Soils	9. High organic matter content in the surface horizon
	10. Streaking of subsurface horizons by organic matter
	11. Organic pans

Problem soils

The "Corps of Engineers Wetlands Delineation Manual" was written for use in all parts of the United States. The manual recognized that there were problematic hydric soils that lacked any of the listed field indicators. It specifically mentioned soils derived from red parent materials and soils with thick, black A horizons. It was also recognized that soils with sandy textures in the surface horizons may not develop iron segregations and that other indicators would have to be used. Several of the chapters in this report address soils that are problematic for wetland delineation, including Mollisols of Minnesota and North Dakota, sandy Spodosols of New Hampshire, and some soils formed in red parent material in Louisiana. Another kind of problem soil addressed in the reports were soils with suspected relict redoximorphic features, especially in Alaska, Texas, and Louisiana.

References

- Environmental Laboratory. (1987). "Corps of Engineers wetlands delineation manual," Technical Report Y-87-1, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.
- Mausbach, M. J. (1994). "Classification of wetland soils for wetland identification," *Soil Survey Horizons* 35, 17-25.
- Soil Survey Staff. (1975). *Soil taxonomy*. Agriculture Handbook 436, U.S. Department of Agriculture, Washington, DC.
- _____. (1994). *Keys to soil taxonomy*. 6th ed., USDA Soil Conservation Service, Washington, DC.
- U.S. Department of Agriculture Soil Conservation Service. (1991). *Hydric soils of the United States*. Misc. Pub. 1491. Washington, DC.
- _____. (1994). *National Food Security Act Manual*. 3d ed., Washington, DC.

2 Preliminary Investigations of Hydric Soil Hydrology and Morphology on the Texas Gulf Coast Prairie¹

Description of the Study Area

This report is a 5-year update of monitoring data from selected sites in Harris, Jefferson, and Victoria counties in the Gulf Coast Prairie Major Land Resource Area (MLRA) (Figure 1). A substantial portion of the information has been reported in a dissertation (Griffin 1991), a guide book (U.S. Department of Agriculture 1990), and in a published paper (Griffin, Wilding, and Drees 1992). Since a massive amount of information has been compiled over this time period, information that is readily available in published reports will be referenced in order to minimize the size of this report.

A total of 14 sites were monitored, 7 of which will be discussed here. These represented five soil series, two of which (China and League) had paired irrigated and nonirrigated sites. Soil classification is given in Table 1. Some of the soil names have been changed since the first report was completed, so the new names have been cross-referenced with the original names, along with present and proposed classification of the soils.

Detailed information on the location, climate, geomorphic setting, soil series, profile descriptions, taxonomy, drainage classes, relationships of the soils to one another, sources of water, and hydrodynamics is contained in Griffin (1991) and U.S. Department of Agriculture (1990). Work on the

¹ Written by Richard W. Griffin, Prairie View A&M University, Prairie View, TX 77446; Larry P. Wilding, Department of Soil and Crop Science, Texas A&M University, College Station, TX 77843; Wesley L. Miller and Gerald W. Crenwelge, USDA Natural Resources Conservation Service, Victoria, TX 77901; Richard J. Tucker, and L. Richard Drees, Department of Soil and Crop Science, Texas A&M University, College Station, TX 77843; and Warren C. Lynn, USDA Natural Resources Conservation Service, National Soil Survey Center, Lincoln, NE 68508-3866.

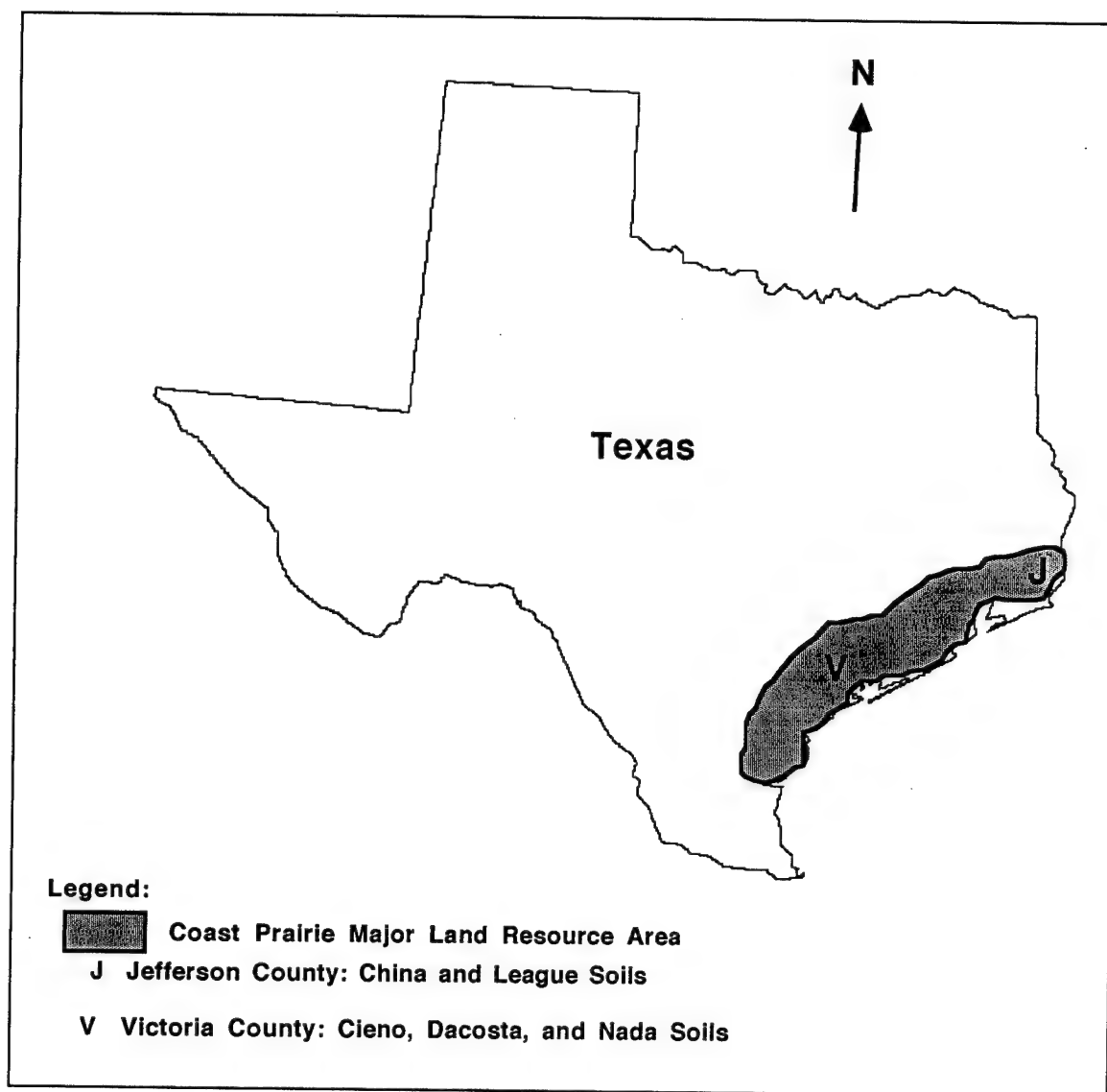


Figure 1. Map of Texas Coast Prairie MLRA with selected soils by county

China and League nonirrigated sites was discontinued in 1991 because of the need to return the areas to crop research.

Methods

Details of the monitoring locations and procedures, measurements taken, instruments used, placement and depth, and monitoring schedule are contained in Griffin (1991) and U.S. Department of Agriculture (1990). Instruments were installed between August and November 1988. Routine physical and chemical soil determinations were made at the National Soil Survey Laboratory (NSSL) of the USDA Natural Resources Conservation Service (NRCS) in

Table 1 Cross-Reference of New and Original Soil Series Names and Present and Proposed Classification of the Soils			
Soil Series Name		County	Present/Proposed Classification
New	Original		
China	Beaumont	Jefferson	Fine, montmorillonitic, hyperthermic Oxyaquic Dystruderts/Epiaquic Dystruderts
Cieno	Cieno	Victoria	Fine-loamy, siliceous, hyperthermic Typic Endoaqualfs/Typic Epiaqualfs
Dacosta	Dacosta	Victoria	Fine, montmorillonitic, hyperthermic Vertic Argiudolls/Epiaquic Vertic Argiudolls
League	Lake Charles	Jefferson	Fine, montmorillonitic, hyperthermic Oxyaquic Dystruderts/Epiaquic Dystruderts
Nada	Nada	Victoria	Fine-loamy, siliceous, hyperthermic Oxyaquic Hapludalfs/Epiaquic Hapludalfs

Lincoln, NE. Physical and chemical data for each soil are listed in Griffin (1991). The project was supported through USDA NRCS project number 68-7442-9-17 and the Texas Agricultural Experiment Station.

Several physical and chemical measurements were made to determine depth, duration, and frequency of saturation and reduction, particularly iron reduction, for each soil. Piezometers consisting of 1.9-cm OD open polyvinyl chloride pipes were installed in triplicate at four depths (25, 50, 100, and 200 cm) and were monitored every 2 weeks for water table fluctuations (Bouma, Dekker, and Haans 1980). Soil moisture potentials were checked and monitored every 2 weeks with jet-filled tensiometers (Richards 1965; Bouma, Baker, and Veneman 1974). Tensiometers were installed in triplicate at three depths in the soils.

During periods when the soil was moist, the presence of ferrous iron in the soil was determined at four depths (0, 25, 50, and 100 cm) by moistening the soil with 0.2-percent α, α' -dipyridyl in 10-percent acetic acid, which produces a pink color when ferrous iron is present in the soil (Childs 1981). After 1990, the α, α' -dipyridyl was adjusted to pH 7 using ammonium acetate so that ferric iron reduction did not occur in the acetic acid, which usually had a pH of 4. The development of pink indicator color within 30-60 sec was recorded in order to eliminate errors associated with the photochemical reduction of ferric-organic complexes associated with readings from longer time periods.

Redox potentials (Eh) and pH were measured on extracted fresh soil cores at four depths (0, 25, 50, and 100 cm) in the soil every 2 weeks. Redox potentials were taken within 1 min using a portable Eh/pH meter reading millivolts and a combination of Pt and calomel electrodes. The Eh measured

at the field pH was converted to values equivalent to the standard hydrogen electrode (SHE) at pH 7 by adding +244 mV to the Eh measurement. The soil pH (measured from saturated paste or moist soil core extract) was measured in order to relate the pH values to the Eh values at each depth in the soil.

Precipitation was measured every 2 weeks at each site with a manual rain gauge. A total of five rain gauges were used to measure the precipitation at eight research sites. Daily rainfall measurements taken by the weather station attendant at the Beaumont Rice Research Station were used for the six sites located in Jefferson county. Official rainfall records collected by the National Weather Service at Beaumont, Waller, and Victoria were used to compare biweekly rainfall records with the 20- to 30-year mean values. Analysis of the precipitation record for 1989 and 1990 in relation to "normal" precipitation is contained in Griffin (1991).

Soil temperature was measured at two depths (50 and 200 cm) at seven sites. The equipment used to measure the soil temperature at these sites was an electronic thermometer and thermistors (wire electrodes) with epoxy tips. In November 1990, oxygen chambers were installed at the China nonirrigated and League nonirrigated sites in duplicate at three depths (25, 50, and 100 cm). Dr. Fred Turner, located at the Beaumont Rice Research Station, collected all of the oxygen measurements used in this study. The method used was similar to the method described in Faulkner, Patrick, and Gambrell (1989).

A number of problems were encountered that were not alleviated or eliminated by the methodology. The inherent spatial variability in the soils caused problems when installing instruments that were supposed to measure the same soil conditions. In the soils with gilgai microtopography, instrument sites were either placed in the microlow or microhigh positions. Differences in the measured values for piezometers, tensiometers, and platinum microelectrodes might have been due to the spatial variability. The most accurate method to characterize these differences will require extraction of the instruments from the soil at the end of the study. Then, a description and tests of the monitored depths will allow comparison between replicates. Crayfish krotovina and their pedotubules were part of the spatial variability that might have affected water table levels, soil moisture potentials, and Eh values. Natural cracks in the soil contribute to bypass flow, which might have affected water table levels and soil moisture potentials. Tensiometer ceramic cups were pushed into an undisturbed soil matrix, which might have produced a smeared instrument-soil interface that did not allow the same water movement as the undisturbed soil. If the soil was not subjected to a wetting and drying cycle, then the smeared interface might remain intact and continue to affect soil moisture potentials. This problem was more likely to occur at depths greater than 50 cm where soil dessication did not result in seasonal volume changes. The tensiometers were filled with water, so during freezing periods the reservoir caps were removed and the stems were emptied to prevent expansion of the side walls. This produced periods in the monitoring scheme when piezometers indicated a

water table present, yet the matric potential values could not be measured. The original portable platinum microelectrode had a standard epoxy covering the junction between the platinum tip and the stainless steel body. The ferrous-ferric standardization solution contained 1 M sulfuric acid, which degraded the epoxy on the microelectrode. Degraded epoxy caused the microelectrode to produce very erroneous negative Eh values. The microelectrodes were reconditioned in 1989 with an acid-proof epoxy that maintained an excellent working condition.

Saturation was based on piezometer data and supported by tensiometer data. On each monitoring date, piezometer data that indicated water table depths with a variance of less than 15 cm were averaged to produce a mean water table. If the water table was less than or equal to 25 cm, the 25-, 50-, 100-, 200-, and 500-cm or deepest piezometer data were used to produce the mean water table. As the water table depth increased, the appropriate piezometer data were used to calculate the mean water table. Generally, if the water table was below 50 cm, the 100- and 200-cm piezometer data proved to be most reliable. If shallower piezometer data did not agree with each other within 15 cm, especially after a rainfall, then an assumption was made that the soil had downward moving water fronts.

Tensiometers generally supported placement of water table depths, but often exhibited saturation for longer periods than piezometers. Tensiometers may have been reflecting soil matrix values even after cracks (macropores) drained because the tensiometers were installed by pushing the ceramic cups into wet soil. Thus, lag effects occur between tensiometer and piezometer responses. The effective cross-sectional area of piezometers was greater than tensiometers, so there was a higher probability that piezometers intercepted more cracks, structural planes, or macrovoids than tensiometers.

Climatic Variation (Precipitation and Temperature)

China and League soils

The 1989 cumulative precipitation for the China and League soils in Jefferson County was 2 percent higher than the 20-year mean for the Beaumont Rice Research Station, which was located approximately 0.8 km from this site (Figure 2). Cumulative precipitation for the site was 10 percent lower than the 20-year mean in 1990, 41 percent higher than the mean in 1991, 3 percent higher than the mean in 1992, and 13 percent lower than the mean as of September 1993. These sites experienced 2 years very close to the 20-year norm, 2 years that were drier than the norm, and 1 year that was extremely wet during this monitoring period.

The mean annual soil temperature (MAST) at 50-cm depth for the China irrigated and nonirrigated sites ranged from 24 to 27 °C during 1989 to 1991, and the overall 3-year average was 25 °C, which corresponded with the

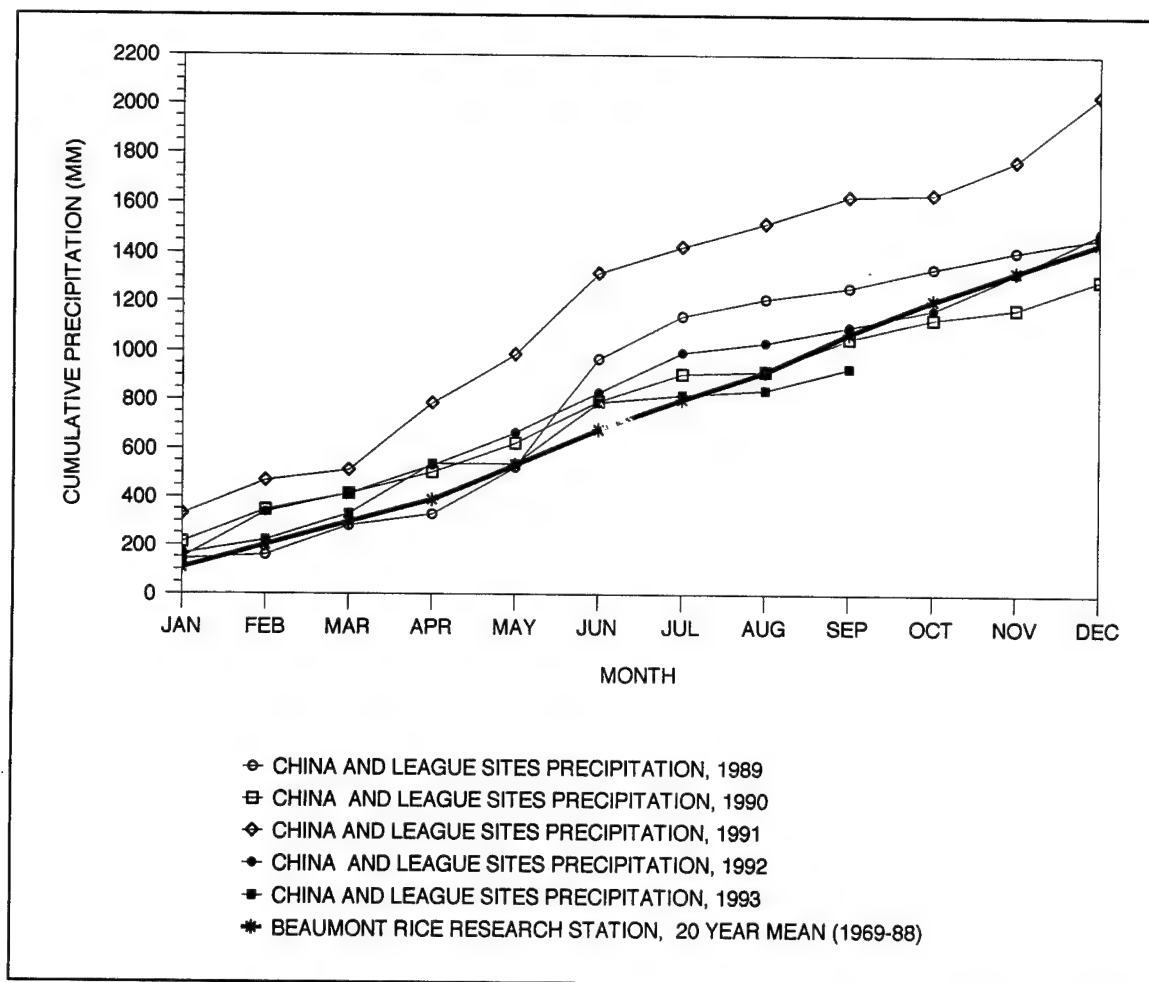


Figure 2. Jefferson County cumulative precipitation by month versus the Beaumont Rice Research Station mean

hyperthermic rather than the thermic temperature regime. Previously, the China and League soils were classified in the thermic temperature regime; therefore, these data conflicted with the previous classification. The MAST at 50-cm depth for the League irrigated and nonirrigated sites ranged from 22 to 27 °C during 1989 to 1993, and the overall 5-year average was 25 °C, which corresponded with the hyperthermic temperature regime.

Cieno and Nada soils

The 1989 cumulative precipitation for the Cieno and Nada soils was 27 percent lower than the 30-year mean for the city of Victoria, TX, which was located approximately 8 km from this site (Figure 3). Cumulative precipitation was 19 percent lower than the 30-year mean in 1990, 41 percent higher than the mean in 1991, 51 percent higher than the mean in 1992, and 16 percent higher than the mean in 1993. These sites experienced 2 years that were

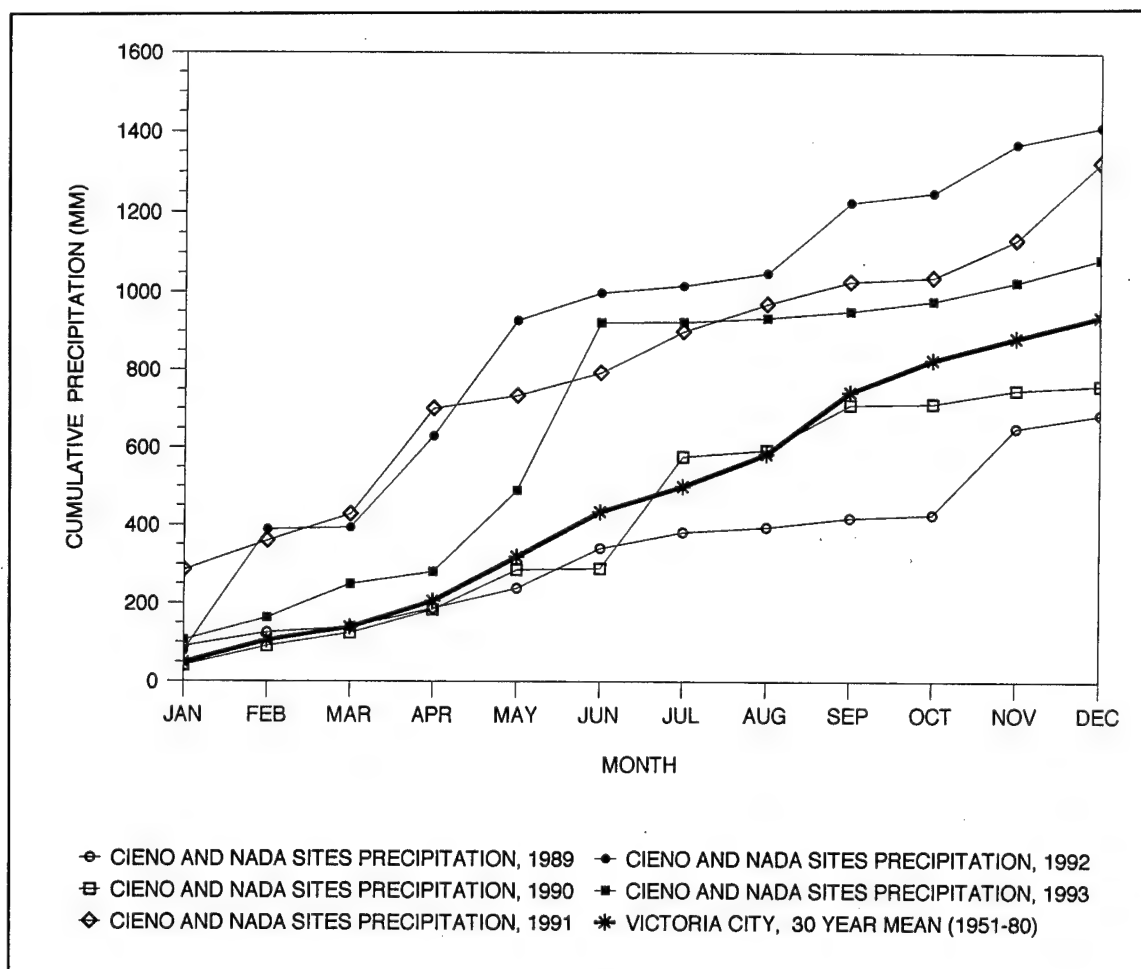


Figure 3. Victoria County cumulative precipitation by month for Cienfo and Nada sites versus the Victoria city mean

significantly drier than the norm and 3 years that were significantly wetter than the norm.

Dacosta soil

The 1989 cumulative precipitation for the Dacosta soil was 26 percent lower than the 30-year mean for the city of Victoria, TX, which was located approximately 8 km from this site (Figure 4). Cumulative precipitation for the site was 1 percent lower than the 30-year mean in 1990, 71 percent higher than the mean in 1991, 31 percent higher than the mean in 1992, and 30 percent higher than the mean in 1993. This site experienced 1 year that was significantly drier than the norm, 1 year that was near the norm, and 3 years that were significantly wetter than the norm.

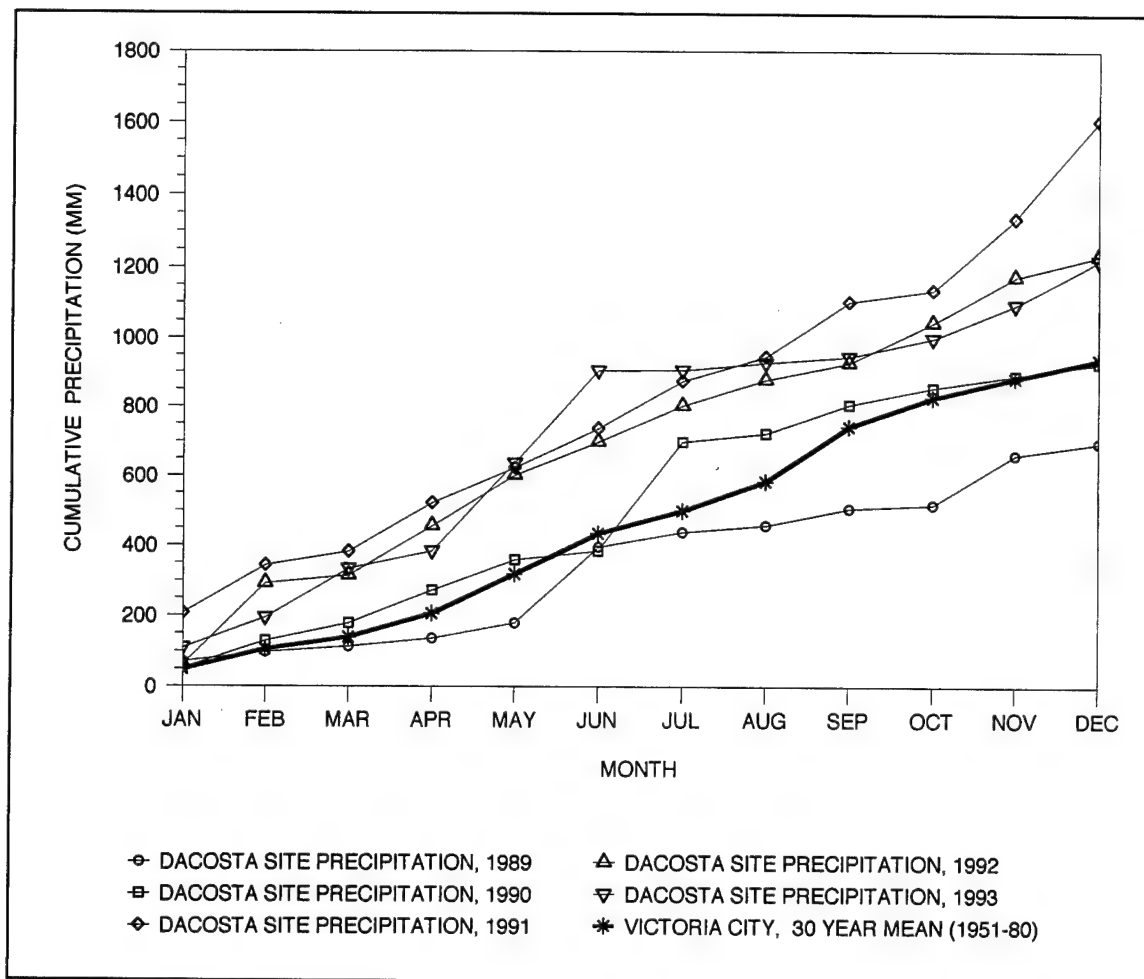


Figure 4. Victoria county cumulative precipitation by month for Dacosta site versus the Victoria city mean

Aquic Conditions and Hydric Status

Criteria for characterizing aquic conditions and the hydric status of soils are similar in some respects, but significant differences exist that create assignment problems for soils in this study. The ferrous iron criterion, which defines reduction in the aquic conditions criteria, differs significantly from the anaerobiosis criterion used for hydric soils. Reduced iron does not exist in the presence of free oxygen, so this criterion is an extreme of the anaerobiosis range, which is defined as the absence of molecular oxygen. Anaerobiosis occurs at much higher Eh values than ferric iron reduction. The ferrous iron criterion is used for aquic conditions because the absence of oxygen is very difficult to measure in field soils, while the presence of reduced iron can be readily detected using the α, α' -dipyridyl dye test. It is also difficult to obtain reliable O_2 measurements due to the long period of equilibration resulting from slow diffusion rates in the soil.

At present, there is no set time limit for the duration or periodicity of saturation in the aquic conditions criteria; however, oxyaquic conditions and hydric status have time limits. For example, oxyaquic conditions require at least 30 days of continuous saturation, and hydric status requires ≥ 7 days of ponding or ≥ 14 days of continuous saturation. There are also no standards for how long and how much of the soil matrix needs to be reduced. Instrument depths used in this study were set up to match key depths given in the aquic conditions criteria. SI units were used, so the aquic conditions depths (25, 50, 100, and 200 cm) did not match depths given in hydric soil criteria (15, 30, 46 cm), and extrapolation may significantly bias the data. An attempt has been made to report the data in the most concise manner bearing in mind that a slight deviation has been made from the original research focus.

Results and Discussion

The original focus of this study in Texas was to monitor moisture regimes to identify aquic conditions in the soils, so the complete soil profile was characterized to define these transient conditions. In this report, the focus has been on the hydric status of the soils, so only the upper 50 cm of the soil is of primary interest. Seven sites will be discussed in this section, so only the most pertinent points will be covered.

China soil

Saturation. The China soil experienced endosaturation with a continuous water table from the upper boundary to more than a 2-m depth. This soil had a nonirrigated and an irrigated site that had similar water table levels during most of the monitoring period, except during flood irrigation periods (June to August). The nonirrigated site was saturated at the 25-cm depth, based on piezometer data, during 53 percent of the 35-month monitoring period and at the 50-cm depth during 79 percent of the period (Table 2). The 25-cm piezometers indicated that the soil was never ponded at the surface, which did not correspond closely with field observations that indicated about 5 cm of ponded water at the site (Figure 5). Based on tensiometer data, the site was saturated (≤ -1 cbar) at the 25-cm depth during 63 percent of the period and at the 50-cm depth during 73 percent of the period. If saturation values of ≤ -2 cbars were used, then the site would be saturated for 8- to 9-percent longer duration than inferred from ≤ -1 cbar readings.

The irrigated site was saturated at the 25-cm depth, based on piezometer data, during 54 percent of the 63-month monitoring period and at the 50-cm depth during 75 percent of the period (Table 2). The 25-cm piezometers indicated that the soil was ponded at the surface during 14 percent of the period (Figure 5). Based on tensiometer data, the site was saturated (≤ -1 cbar) at the 25-cm depth during 70 percent of the period and at the 50-cm depth during 88 percent of the period. If saturation values of

Table 2**Percentage of the Monitoring Period That Soils Were Ponded, Saturated, or Reduced at the Indicated Depth**

Characteristic	Monitoring Site						
	China Nonirrigated	China Irrigated	League Nonirrigated	League Irrigated	Cieno	Nada	Dacosta
Ponded (P25) ¹	0	14	3	13	36	6	0
Saturated at ≤15 cm (P25) ²	30	37	32	41	--	--	--
Saturated at 25 cm (P25/50)	53	54	52	58	53	18	24
Saturated at 25 cm (≤-1 cbar) (T25)	63	70	58	71	56	28	28
Saturated at 25 cm (≤-2 cbar) (T25)	71	74	66	77	57	33	33
Saturated at 50 cm (P50)	79	75	73	76	62	13	14
Saturated at 50 cm (≤-1 cbar) (T50)	73	88	74	94	55	10	25
Saturated at 50 cm (≤-2 cbar) (T50)	82	89	77	96	59	13	29
Reduced at 0 cm ³	7	22	18	22	33	16	14
Reduced at 25 cm	8	13	3	10	28	9	2
Reduced at 50 cm	5	9	1	7	14	4	0
Reduced at 100 cm	3	21	5	2	2	0	0

¹ Instrument used, where P25 = piezometer 25-cm depth, P25/50 = piezometer at either 25- or 50-cm depth, T25 = tensiometer at 25-cm depth, and T50 = tensiometer at 50-cm depth.

² Includes ponding, if present.

³ According to α, α' -dipyridyl test for presence of ferrous iron.

≤ -2 cbars were used, then the site would be saturated for 1- to 4-percent longer duration than inferred from ≤ -1 cbar readings.

Reduction. The nonirrigated site had observations of reduced iron present in the upper 50 cm during 5 to 8 percent of the monitoring period, and the irrigated site had observations of reduced iron present in the upper 50 cm during 9-22 percent of the period (Table 2). The reduction at 100 cm for the nonirrigated and irrigated sites ranged from 3-21 percent. These data reflect much longer periods of saturation than periods of reduction in the upper

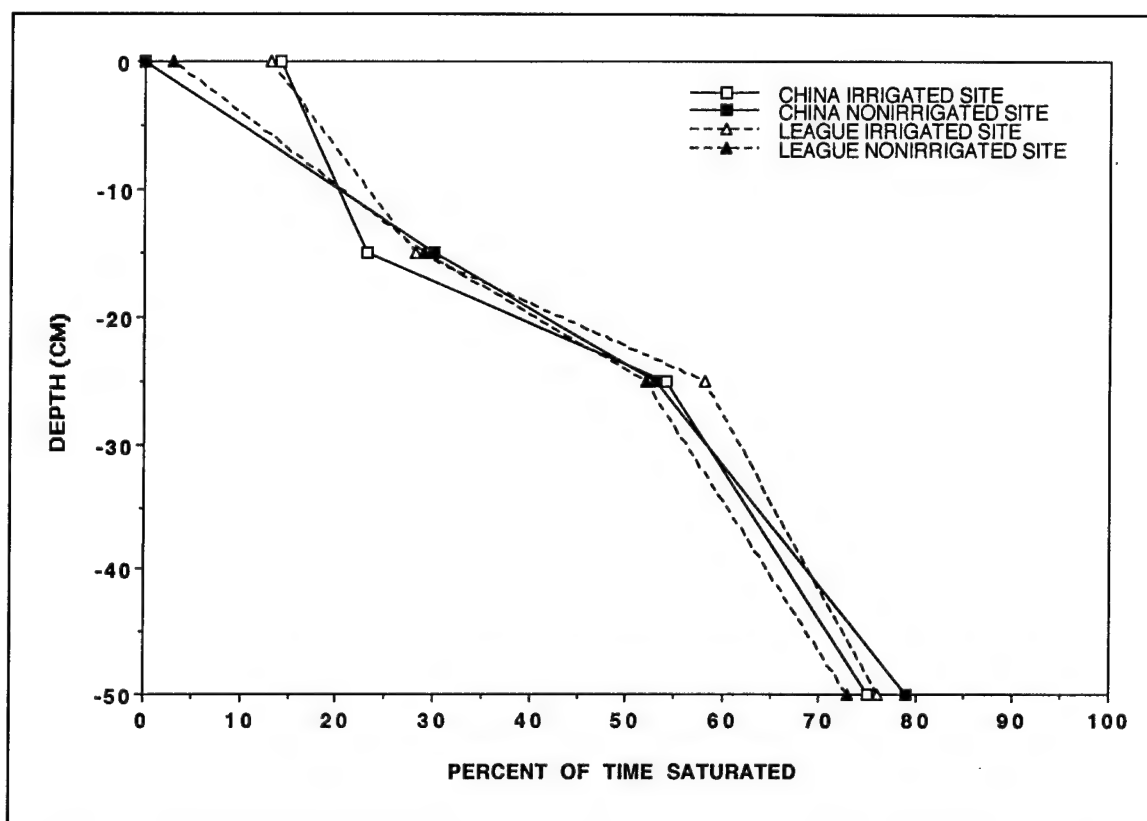


Figure 5. Percentage of time soil was saturated versus depth for the Jefferson County sites, based on piezometer data

50 cm. Based on piezometers, the soil was saturated 41-74 percent longer than it was reduced. These data indicate that this soil experienced significant periods of oxyaquic conditions, because the soil was saturated, but not reduced. Since the periods when the soil was reduced were not sufficient to meet aquic conditions, the soil was classified as oxyaquic. Reduction during the warm season occurred below the water table as well as within the capillary fringe above the water table. Ferrous iron was observed at heights of 10-30 cm above the defined water table. However, this observation cannot be easily extrapolated to indicate a reduced zone above the water table, because these soils exhibit a greater amount of microsite reduction than whole soil matrix reduction events.

The League soil will be used as the model for Jefferson County to illustrate the extent of anaerobiosis based on redox potential values for the 63-month period. The following limited set of redox potential measurements for the China nonirrigated site during a 26-month period from October 1988 to December 1990 is also available in the publication by Griffin (1991). Eh values, which averaged about 540 mV and ranged from 260 to 650 mV, were not closely correlated with water table depth. At the soil pH of 5.5, Fe^{3+} would be reduced to Fe^{2+} at Eh values less than or at about +235 mV.

These data indicated this site had oxidized conditions from October 1989 to December 1990, which closely correlated with the absence of positive tests for ferrous iron. Corresponding Eh data during the warm season (April to September 1989) when reduction of iron occurred were not available because of equipment failures.

The O₂ content at 25 and 50 cm did not closely reflect either water table depth or matric potential values (Griffin 1991). However, when ferrous iron was present at microsites within the upper 100 cm from April to September 1989, the O₂ content at 50 cm decreased to a minimum of 6 percent. These data indicated anaerobic conditions at microsites where ferrous iron was present, even though the soil matrix had low-to-moderate O₂ contents. The lack of close correlation may have been due to very slow diffusivity of gas through these fine-textured soil materials such that equilibrium of O₂ in the oxygen chamber was not achieved for periods ranging from 7 to 14 days. This lag effect indicated that gas compositions represent long-term averages rather than real-time data. Additionally, periodic influxes of oxygenated rainfall may have alleviated anaerobic conditions.

Temperature. The effects of soil temperature on timing of anaerobiosis and reduction has been more closely defined in this project. Additional study will be required to produce better quantitative relationships. At this time, the belief is that three "windows" or short periods have been identified when reduction of iron should be observed on the Texas Gulf Coast Prairie. In the spring, the highest potential for reduction of iron is believed to occur during March to April, with a slightly lower probability during late February to early May. In the fall, the highest potential for reduction of iron is believed to occur during August to September, with a slightly lower probability during late September to early November. The spring "window" may be more closely related to temperature than the fall "window." The growing season inferred from soil temperature regimes and from the air temperature thresholds do not appear to have a significant effect on the soil microbiological activity in this part of Texas. Identification has not been made regarding whether these "windows" are strongly linked to a specific temperature or range of temperatures, because of the belief that microbes can function during the entire year in this area of Texas. The presence of labile organic carbon and specific moisture conditions are thought to be the primary factors in conjunction with the microbes that drive the soil into a reduced iron state. The third window occurs when rainfall from hurricanes or tropical storms results in significant ponding during May to September, which occurred on two occasions during the monitoring period.

Hydric status. The China soil does not fit hydric criteria based on the following: (a) the soil is presently classified as an Oxyaquic Dystrudert and the proposed class is Epiaquic Dystruderts (Table 1); (b) the soil is designated as somewhat poorly drained, but does not have a frequently occurring (≥ 50 times in 100 years) water table at less than 15 cm for a significant period during the growing season (Soil Survey Division Staff 1993); (c) the soil is not frequently ponded for long duration (7-30 days) or very long

duration (≥ 1 month) during the growing season; and (d) the soil is not frequently flooded for long duration or very long duration during the growing season. Despite being saturated at ≤ 15 cm for 30 percent of readings, the nonirrigated China soil rarely gave a positive ferrous iron test (Table 2). Therefore, there was little evidence that this soil satisfied the definition of a hydric soil, that it is "saturated, flooded, or ponded long enough during the growing season to develop anaerobic conditions in the upper part" (U.S. Department of Agriculture Soil Conservation Service 1991).

Redoximorphic features. Macromorphic redoximorphic features in the upper 50-cm zone (A horizons) of the China soil included dominant matrix colors of 4/1 with few to common distinct (5YR and 7.5YR 5/8) soft masses of Fe and Fe-Mn segregations (Griffin 1991). Micromorphic features included common vugh and channel ferrans and neoferrans and common regular Fe-Mn nodules with embedded skeleton grains. For this soil and the soils that follow, nodules with diffuse boundaries were indicative of active formation. Nodules with sharp boundaries might have been moved to their present position or formed during paleo-periods, so they may not reflect contemporaneous conditions.

In the China soil, it is difficult to identify any morphological features that distinguish horizons that are usually above the water table, but are within the capillary fringe, because the soil is saturated for significant periods in the upper 50 cm. Neoferrans, most likely ferrihydrite, reached a maximum in the upper 50 cm and correlated well with seasonal fluctuation of the water table, and may have indicated that more oxalate iron was mobile and subject to reduction and precipitation (Wang et al. 1993).

League soil

Saturation. The League soil experienced endosaturation with a continuous water table from the upper boundary to more than a 2-m depth. This soil had a nonirrigated and an irrigated site that had similar water table levels during most of the monitoring period, except during flood irrigation periods (June to August) (Figure 5). The nonirrigated site was saturated at the 25-cm depth, based on piezometer data, during 52 percent of the 35-month monitoring period and at the 50-cm depth during 73 percent of the period (Table 2). The 25-cm piezometers indicated that the soil was ponded at the surface during 3 percent of the period (Figure 5). Based on tensiometer data, the site was saturated (≤ -1 cbar) at the 25-cm depth during 58 percent of the period and at the 50-cm depth during 74 percent of the period. If saturation values of ≤ -2 cbars were used, then the site would be saturated for 3- to 8-percent longer duration than inferred from ≤ -1 cbar tensiometer readings.

The irrigated site was saturated at the 25-cm depth, based on piezometer data, during 52 percent of the 63-month monitoring period and at the 50-cm depth during 76 percent of the period (Table 2). The 25-cm piezometers indicated that the soil was ponded at the surface during 13 percent of the

period (Figure 6). This observation reflects the periods of flood irrigation for the irrigated site. Based on tensiometer data, the site was saturated (≤ -1 cbar) at the 25-cm depth during 71 percent of the period and at the 50-cm depth during 94 percent of the period. If saturation values of ≤ -2 cbars were used, then the site would be saturated for 2- to 6-percent longer duration than the ≤ -1 cbar tensiometer readings.

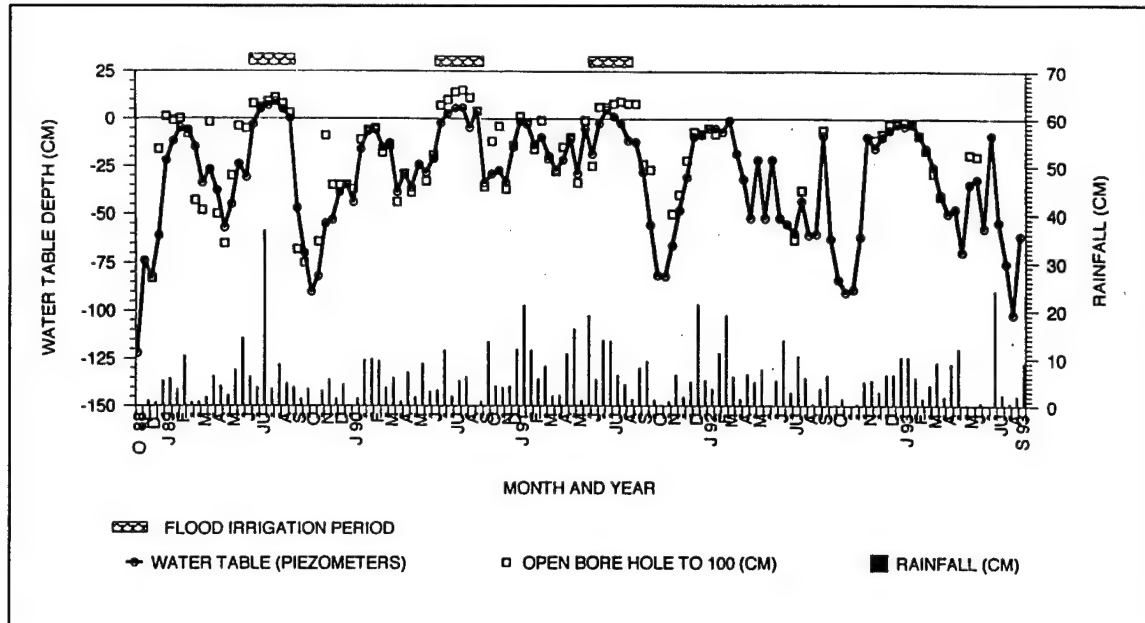


Figure 6. Water table depth versus rainfall by month and year for the League soil (irrigated site)

Reduction. The nonirrigated site had observations of reduced iron present in the upper 50 cm during 1-18 percent of the monitoring period, and the irrigated site had observations of reduced iron present in the upper 50 cm during 7-22 percent of the period (Table 2). The League nonirrigated and irrigated sites at 100 cm had observation of reduction during 2-5 percent of the period. Based on piezometers in the upper 50 cm, the soil was saturated from 48-72 percent longer than it was reduced. These data indicate that this soil experienced significant periods of oxyaquic conditions, because the soil was saturated, but not reduced. Since the periods when the soil was reduced were not sufficient to meet aquic conditions, the soil was classified as oxy-aquic. Reduction during the warm season occurred below the water table as well as within the capillary fringe above the water table.

The League soil was used as the model for Jefferson County to illustrate the extent of anaerobiosis based on redox potential values for the 63-month period. At the nonirrigated site, the Eh values in the upper 50 cm, which averaged about 300 mV, ranged from -406 to 704 mV, but were not closely correlated with water table depth. At the soil pH of 7.0, Fe^{3+} would be reduced to Fe^{2+} at Eh values less than or about $+145$ mV. This site had dominantly oxidized conditions, which were not closely correlated with the

presence of positive tests for ferrous iron. During one specific period, June-August 1990, Eh values dropped below +145 mV, which closely correlated with the presence of positive tests for ferrous iron and periods of flood irrigation. The presence of ferrous iron correlated with the higher contents of organic matter and management practices, such as rough plowing, at the soil surface which favored localized ponding of water on man-induced plow pans in the lower A horizons.

The O₂ content at 25- and 50-cm depths did not closely correlate with either water table depth or matric potential values. However, when ferrous iron was present within the upper 100 cm from April to August 1989, the O₂ content at 25- and 50-cm depths decreased to a minimum of 9 and 3 percent, respectively. These data indicated anaerobic conditions at microsites where ferrous iron was present, although the soil matrix had low-to-moderate O₂ contents.

Hydric status. The League soil does not fit the hydric criteria based on the following: (a) the soil is presently classified as an Oxyaquic Dystrudert and the proposed class is Epiaquic Dystruderts (Table 1); (b) the soil is somewhat poorly drained, but does not have a frequently occurring water table at less than 15 cm for a significant period during the growing season; (c) the soil is not frequently ponded for long duration or very long duration during the growing season; and (d) the soil is not frequently flooded for long or very long duration during the growing season. However, the nonirrigated soil was saturated at ≤ 15 cm for 32 percent of readings and was reduced at the surface 18 percent of the time (Table 2).

Redoximorphic features. Macromorphic redoximorphic features in the upper 50-cm zone (A horizons) of the League soil included dominant matrix colors of 4/1 (Ap only) with few to common distinct (7.5YR and 10YR 5/3 to 5/6) soft masses of Fe and Fe-Mn. Micromorphic features included few vugh and channel ferrans and neoferrans, few planar void neoferromangans, and few regular Fe-Mn nodules and concretions with embedded skeleton grains. There were fewer redoximorphic features in the upper 50 cm as compared with the China soil. This observation may be related to the higher pH and lower levels of oxalate iron in the League soil.

The low (1) chroma matrix colors with high (4 to 7) values were indicative of saturated and reduced conditions, which were verified in this soil. The soft masses, mainly Fe and Fe-Mn segregations, were constant with depth, which correlated with the seasonal fluctuation of the water table and the corresponding alternation of reduced and oxidized conditions within the soil. The colors of the Fe and Fe-Mn soft masses became yellower with depth, which correlated with the increased periods of wetness in the lower profile since this soil had a fluctuating groundwater table. The reason for the yellower iron oxides in the lower part of the sola may be related to lower oxalate extractable iron contents associated with ferrihydrite and lepidocrocite. However, this argument appeared to conflict with recorded periods of decreased iron reduction in lower portions of the profile based on α, α' -dipyridyl measurements.

Cieno soil

Saturation. The Cieno soil experienced endosaturation with a continuous water table from the upper boundary to more than a 2-m depth, but dominantly the zone between 1 and 2 m was dry. This soil was saturated at the 25-cm depth, based on piezometer data, during 53 percent of the 63-month monitoring period and at the 50-cm depth during 62 percent of the period (Table 2). The 25-cm piezometers indicated that the soil was ponded at the surface during 36 percent of the period (Figure 7). Based on tensiometer data, the site was saturated (≤ -1 cbar) at the 25-cm depth during 56 percent of the period and at the 50-cm depth during 55 percent of the period. If saturation values of ≤ -2 cbars were used, then the site would be saturated for 1- to 4-percent longer duration than inferred from the ≤ -1 cbar tensiometer readings.

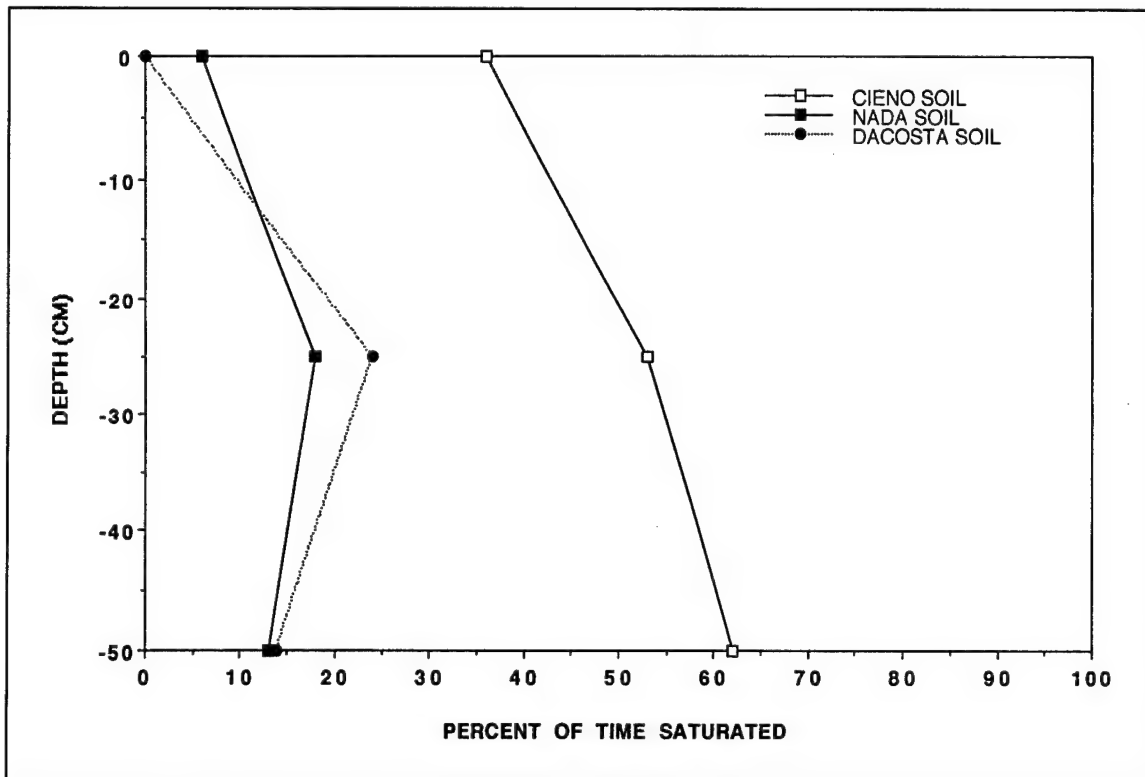


Figure 7. Percentage of time soil was saturated versus depth for the Victoria County sites, based on piezometer data

Reduction. The soil had observations of reduced iron present in the upper 50 cm during 14-33 percent of the monitoring period (Table 2). The Cieno soil had observations of ferrous iron at 100 cm during 2 percent of the period. Based on piezometers, the soil was saturated from 25 to 48 percent longer than it was reduced. These data indicate that this soil experienced periods of oxyaquic conditions, because the soil was saturated, but not reduced. Because the periods when the soil was reduced were sufficient to meet aquic

conditions, the soil was classified as aquic at the suborder level. Reduction during the warm season occurred below the water table as well as within the capillary fringe above the water table.

The Eh values averaged about 432 mV and ranged from -203 to 825 mV. At the soil pH of 5.5, Fe^{3+} would be reduced to Fe^{2+} at Eh values less than or about +235 mV. Redox data support dominantly oxidized conditions; however, significant reduced conditions occurred that were reflected in the saturation and reduction data.

Reduction occurred in the upper part of many of the Gulf Coast Prairie soils for brief periods, and in most cases, except Cieno, less than 50 percent of the matrix was reduced (based on the α, α' -dipyridyl test) in the upper 25 cm of the soils. The number of days of ponding or saturation before Fe^{2+} was observed using α, α' -dipyridyl by depth in the Cieno soil indicated a range of 2-14 days in the 0- to 5-cm zone (Table 3). This period was slightly longer than the Nada soil, because the Cieno soil became ponded initially in December to January, so biologic activity might have been slower during this time period. The 25-cm depth was the same as the Nada soil with a range of 14-28 days. The 50-cm depth had a lower value of 14 days, but the upper value was 56 days, which was the same as the Nada soil. The 100-cm depth indicated a range of 56-112 days. Oxidized rhizospheres in the soil matrix along living roots were first observed in the upper 25 cm of the soil after periods of 4-8 weeks of ponding/saturation. Over 50 percent of the soil matrix in the upper 25 cm was reduced after ponding/saturation for 6-8 weeks.

Table 3
Number of Days of Ponding/Saturation Before Ferrous Iron Was Detected With the α, α' -Dipyridyl Test

Depth, cm	Soil Name	
	Cieno	Nada
0 - 5	2 - 14	1 - 7
25	14 - 28	14 - 28
50	14 - 56	28 - 56
100	56 - 112	--

Hydric status. The Cieno soil satisfies hydric soil criteria based on the following: (a) the soil is presently classified as a Typic Endoaqualf and the proposed class is Typic Epiaqualfs (Table 1); (b) the soil is poorly drained and has a frequently occurring water table at less than 46 cm for a significant period during the growing season; and (c) the soil is frequently ponded for long or very long duration during the growing season.

Redoximorphic features. Macromorphic redoximorphic features in the upper 50-cm zone (A to upper Btg horizon) of the Cieno soil included dominant matrix colors of 4/1 to 6/2 with common to many distinct (2.5YR, 7.5YR, and 10YR 4/6 to 7/2) soft masses of Fe and Fe-Mn segregations with some soft masses occurring along root channels. Micromorphic features included few vugh and channel ferrans and neoferrans and few to common regular Fe-Mn nodules that had sharp and diffuse boundaries.

The Cieno soil had a perched water table that ranged from an upper limit near the soil surface to a lower limit about 100 cm below the soil surface. The redoximorphic features generally supported the wetness conditions in the upper part of this soil. The low (1 to 2) chroma matrix colors with high (4 to 6) values were indicative of saturated and reduced conditions that were verified in this soil. The soft masses, mainly Fe and Fe-Mn segregations, decreased with depth, which correlated with the seasonally perched water table and the corresponding alternation of reduced and oxidized conditions within the perched zone in this soil. The colors of the soft masses became yellower with depth similar to the China soil. This observation may correlate with differences in the types and stabilities of iron oxides present and/or with differences in the duration of saturation in the lower profile, since this soil had a perched water table.

Nada soil

Saturation. This soil was saturated at the 25-cm depth, based on piezometer data, during 19 percent of the 63-month monitoring period and at the 50-cm depth during 2 percent of the period (Table 2). The 25-cm piezometers indicated that the soil was ponded at the surface during 6 percent of the period (Figure 7). Based on tensiometer data, the site was saturated (≤ -1 cbar) at the 25-cm depth during 28 percent of the period and at the 50-cm depth during 10 percent of the period. If saturation values of ≤ -2 cbars were used, then the site would be saturated for 3- to 5-percent longer duration than the ≤ -1 cbar tensiometer readings.

Reduction. The soil had observations of reduced iron present in the upper 50 cm during 4-16 percent of the monitoring period (Table 2). The Nada soil never had any observations of ferrous iron at 100 cm during the period. Based on piezometers, the soil was saturated from 10-22 percent longer than it was reduced. These data indicate that this soil experienced a few periods of oxyaquic conditions, because the soil was saturated, but not reduced. Since the periods when the soil was reduced were not sufficient to meet aquic conditions, the soil was classified as oxyaquic.

The number of days of ponding or saturation before Fe^{2+} was observed using α, α' -dipyridyl by depth in the Nada soil indicated a range of 1-7 days in the 0- to 5-cm zone (Table 3). The 25-cm depth was the same as the Cieno soil with a range of 14-28 days. The 50-cm depth had a lower value of 28 days, but the upper value was 56 days, which was the same as the Cieno

soil. At the 100-cm depth, there were no observations of ferrous iron during the monitoring period. Oxidized rhizospheres in the soil matrix along living roots were first observed in the upper 25 cm of the soil after periods of 4-8 weeks of ponding/saturation, which was the same as the Cieno soil. In most years, the upper 25 cm of the Nada soil matrix was reduced less than 50 percent during the wet periods. After 4-12 weeks of ponding/saturation during the wettest season, most of the upper 25 cm of the soil matrix changed color from dark grayish brown (10YR 4/2) to dark gray (5Y 4/1 and 10YR 4/1).

Hydric status. The Nada soil does not fit the hydric criteria based on the following: (a) the soil is presently classified as an Oxyaquic Hapludalf and the proposed class is Epiaquic Hapludalfs (Table 1); (b) the soil is somewhat poorly drained, but does not have a frequently occurring water table at less than 15 cm for a significant period during the growing season; and (c) the soil is not frequently ponded or flooded for long or very long duration during the growing season. However, the Nada soil tested positive for ferrous iron at the surface in 16 percent of measurements (Table 2).

Redoximorphic features. Macromorphic redoximorphic features in the upper 50-cm zone (A and upper Btg horizons) of the Nada soil included dominant matrix colors of 4/1 to 6/2 with few distinct (7.5YR 4/4) soft masses of Fe and Fe-Mn segregations with some soft masses occurring along root channels and few 1 chroma clay films. Micromorphic features included few vugh and channel ferrans and neoferrans and few regular Fe-Mn nodules with embedded skeleton grains.

The Nada soil exhibited episaturation with a perched water table that had an upper limit near 25 cm and a lower limit that was near 50 cm below the soil surface for brief periods in the winter and early spring. The water table was perched in the upper part of the dispersed Bt horizon or at the contact with this very slowly permeable horizon. Above the Bt horizon, the colors were indicative of saturation, but did not closely correspond with reduction. Below the Bt horizon, the colors did not correspond with present conditions. The redoximorphic features did not generally support the wetness conditions in the upper part of the soil. The low (1 to 2) chroma matrix colors with high (4 to 6) values used as indicators of saturated and reduced conditions were only verified for brief periods in this soil.

Dacosta soil

Saturation. This soil was saturated at the 25-cm depth, based on piezometer data, during 24 percent of the 63-month monitoring period and at the 50-cm depth during 14 percent of the period (Table 2). The 25-cm piezometers indicated that the soil was never ponded at the surface (Figure 7). Based on tensiometer data, the site was saturated (≤ -1 cbar) at the 25-cm depth during 28 percent of the period and at the 50-cm depth during 25 percent of the period. If saturation values of ≤ -2 cbars were used, then the site

would be saturated for 4- to 5-percent longer duration than inferred from the ≤ -1 cbar tensiometer readings.

Reduction. The soil had observations of reduced iron present in the upper 50 cm during 2-14 percent of the monitoring period (Table 2). The soil never had any observations of reduced iron at 50 or 100 cm during the period. Based on piezometers, the soil was saturated from 14-22 percent longer than it was reduced. These data indicate that this soil experienced a few periods of oxyaquic conditions, because the soil was saturated, but not reduced. Since the periods when the soil was reduced were not sufficient to meet aquic conditions and the oxyaquic conditions were of short duration, the soil was classified as vertic rather than aquic or oxyaquic.

Hydric status. Dacosta soil does not fit the hydric criteria based on the following: (a) the soil is presently classified as a Vertic Argiudoll and proposed class is Epiaquic Vertic Argiudolls (Table 1); (b) the soil is moderately well drained; and (c) it is not frequently ponded or flooded for long or very long duration during growing season. However, even this soil tested positive for ferrous iron at the surface in 14 percent of measurements (Table 2).

Redoximorphic features. Macromorphic redoximorphic features in the upper 50-cm zone (A and upper Btg horizon) of the Dacosta soil included dominant matrix colors of 4/1 with few faint (10YR 4/6) soft masses of Fe and Fe-Mn segregations and few Fe-Mn concretions. Micromorphic features included few vugh and channel neoferrans and quasiferrans, few simple and compound micritic calcite nodules with associated ferrans and neoferrans, few regular Fe-Mn nodules, and few regular Fe-Mn concretions with embedded skeleton grains.

The Dacosta soil exhibited brief periods of episaturation with a perched water table that had an upper limit near 25 cm and a lower limit that was near 50 cm below the soil surface. The redoximorphic features generally supported seasonally wet conditions in the upper part of the soil. The low (1 to 2) chroma matrix colors with high (4 to 6) values were indicative of seasonally saturated conditions, which were verified in the 25- to 50-cm zone of this soil. The low-chroma colors in other layers reflect reduced conditions along with the saturated conditions, but these conditions could not be confirmed below 50 cm. The scarcity of observations of reduced iron during 1989 and 1990 favored the hypothesis that the redoximorphic features may be relicts from a wetter period. However, the conclusion about relict redoximorphic features may need to be tempered, since the soil was reduced and saturated during the 1991 to 1993 period, which was much wetter.

Quasi-ferrans only observed in the upper 50 cm were correlated well with the seasonally perched water table, but did not correlate well with the oxidized conditions observed in the soil during the earlier part of the monitoring period. Obviously, this soil represents the "borderline oxyaquic/epiaquic" moisture conditions because the soil experienced a few periods of alternating

oxidation and reduction conditions, but the periods are considered too limited to place the soil in either the oxyaquic or aquic categories.

Summary and Preliminary Conclusions

A 5-year update of monitoring data from seven research sites in the Gulf Coast Prairie MLRA of East Texas was completed to provide data on the hydric status of soils with seasonally wet conditions that are transitional between uplands and coastal marshes. Research on the Texas Gulf Coast during the past 15 years has demonstrated the following: (a) saturation of soil systems does not necessarily equate with anaerobic or oxygen-deficient soil systems, because biological reduction may be limited by suitable organic C for microbial activity; (b) reduction in soils is highly dynamic, microsite specific, and difficult to measure accurately by traditional means; (c) soil color patterns do not necessarily reflect current wetland conditions, but may indicate relict wetness; and (d) the hydrological characteristics of agricultural soil systems have been significantly altered by cultivation practices and hence do not reflect natural precultivated habitats.

As preliminary conclusions, this update has verified the following: (a) the presence of soils with various aquic conditions (Epiaquic suborder and subgroups and Oxyaquic subgroups) in the Texas Coast Prairie MLRA; (b) sporadic, microsite occurrence of ferrous iron in soil systems that were saturated; (c) soils that were saturated for significant periods that nevertheless had no evidence of ferrous iron in the soils; and (d) only one soil clearly met hydric soil criteria based on inundation or saturation; however, other soils appeared to satisfy the hydric soil definition by becoming "anaerobic in the upper part." Significant differences between criteria for characterizing aquic conditions and the hydric status of soils created classification problems in this study. There continues to be ample opportunity to quantify aquic conditions and hydric status of soils in Texas.

References

- Bouma, J., Baker, F. G., and Veneman, P. L. M. (1974). "Measurement in soil pedons above a water table," University of Wisconsin Geological Natural History Survey, Information Circular 27, Madison, WI.
- Bouma, J., Dekker, L. W., and Haans, J. C. F. M. (1980). "Measurement of depth to water table in a heavy clay soil," *Soil Science* 130, 264-270.
- Childs, C. W. (1981). "Field test for ferrous iron and ferric-organic complexes (on exchange sites or in water-soluble forms) in soils," *Aust. J. Soil Res.* 19, 175-180.

- Faulkner, S. P., Patrick, W. H., Jr., and Gambrell, R. P. (1989). "Field techniques for measuring wetland soil parameters," *Soil Sci. Soc. Am. J.* 53, 883-890.
- Griffin, R. W. (1991). "A study of aquic conditions of seasonally wet soils on the Coast Prairie of Texas," Ph.D. diss., Texas A&M University, College Station, TX.
- Griffin, R. W., Wilding, L. P., and Drees, L. R. (1992). "Relating morphological properties to wetness conditions in the Gulf Coast Prairie of Texas." *Proceedings of the eighth international soil correlation meeting (VIII ISCOM): Characterization, classification, and utilization of wet soils.* J. M. Kimble, ed., USDA Soil Conservation Service, National Soil Survey Center, Lincoln, NE.
- Richards, S. J. (1965). "Soil suction measurements with tensiometers." *Methods of soil analysis, part I.* C. A. Black, ed., Agron. Monogr. 9. Am. Soc. Agron., Madison, WI.
- Soil Survey Division Staff. (1993). *Soil survey manual.* Agriculture Handbook No. 18., U.S. Government Printing Office, Washington, DC.
- U.S. Department of Agriculture. (1990). VIIIth International Soil Correlation Meeting Guidebook for Texas. Soil Conservation Service. (unpublished).
- U.S. Department of Agriculture Soil Conservation Service. (1991). *Hydric soils of the United States.* Miscellaneous Publication 1491, Washington, DC.
- Wang, H. D., White, G. N., Turner, F. T., and Dixon, J. B. (1993). "Ferrihydrite, lepidocrocite, and goethite in coatings from East Texas vertic soils," *Soil Sci. Soc. Am. J.* 57, 1381-1386.

3 Seasonally Wet Soils of Louisiana¹

Introduction

Nine sites were selected for instrumentation in Louisiana as part of the VIII International Soil Correlation Meeting emphasizing Management of Wet Soils (ICOMAC) sponsored by the U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) with continued funding from the NRCS's Global Warming Project. Figure 1 shows a map of Louisiana with the study area highlighted. Table 1 lists all nine soil series and their taxonomic classification. Table 2 presents the location, geological unit, and land use of the study soils.

This report contains selected data on six of these soils from 1989 through 1993. Detailed data are presented for only a few soils to provide representative examples of the kinds of data being obtained and to highlight some significant findings. Study sites were representative of three land resource areas: (a) recent Mississippi River deposits, (b) Red River deposits, and (c) Pleistocene coastal plain deposits and two sites that have a thin Peoria loess cap.

Site Instrumentation and Measurements

Each site was fenced with galvanized wire that enclosed a 10- by 10-m square plot next to the place where the pit for soil characterization was excavated. Rainfall was measured with a rain gauge. The accumulated rainfall records as well as the other measurements were taken every 2 weeks, or whenever required. Rainfall data were complemented by daily rainfall records from Livingston (Livingston Parish) and Moss Bluff (Calcasieu Parish) meteorological stations.

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Figure 1. Map of Louisiana outlining study area

Water table depths were determined with piezometers. Piezometers were constructed from 1.9-cm OD polyvinyl chloride pipe (Szögi and Hudnall 1992). Pipes were installed in triplicate at depths of 0.25, 0.50, 1.00, and 2.00 m. Water levels in the piezometers were measured by the "hot air method" (Reeve 1986).

Water tension was measured in triplicate with jet-filled tensiometers (Soil Moisture Corporation, Santa Barbara, CA) placed into the soils at three different depths (0.25, 0.50 and 1.00 m). The original gauges were substituted by a Swagelok brass fitting (Swagelok Company, Solon, OH) connected to a rubber septum by a 1.5-cm piece of nylon tubing. Soil suction was measured through the septum with a tensiometer (Soil Measurement Systems, Tucson, AZ).

Reduction was characterized by measuring redox potentials directly with permanently installed platinum electrodes and indirectly by the presence of

Table 1 Classification of the Soils	
Soil Series	Taxonomic Classification
Commerce	Fine-silty, mixed, hyperthermic Aeric Endoaquepts
Sharkey	Very-fine, montmorillonitic, hyperthermic Chromic Epiaquepts
Fausse	Very-fine, montmorillonitic, nonacid, hyperthermic Typic Fluvaquepts
Verdun	Fine-silty, mixed, hyperthermic Albic Glossic Natraqualfs
Crowley	Fine, montmorillonitic, hyperthermic Typic Albaqualfs
Lebeau	Very-fine, montmorillonitic, hyperthermic Aeric Epiaquepts
Moreland	Fine, mixed, thermic Typic Epiaquepts
Beauregard	Fine-silty, siliceous, hyperthermic Plinthic Paleaqualfs
Brimstone	Fine-silty, mixed, hyperthermic Typic Natraqualfs

reduced iron tested with dyes in the field. Platinum electrodes were fabricated according to Szögi and Hudnall (1992). The electrodes were tested in the laboratory in a pH-buffered quinhydrone solution (Jones 1966). Electrodes were installed in the field at 0.50- and 1.00-m depths in triplicate, in order to monitor the redox potential in the soil moisture control section and at diagnostic depths used in *Soil Taxonomy* (Soil Survey Staff 1975).

Redox potentials taken in the field were adjusted by adding +244 mV in order to base redox potentials on the standard hydrogen reference electrode (SHE) for Eh readings. A few redox measurements were taken with platinum electrodes in the topsoil of every soil when they were saturated for several weeks to complement the information on soil reduction. A soil was considered to be reduced with respect to iron when the redox potential was below 150 mV. Interpretation was made without pH correction and was based on redox ranges given by Patrick and Mahapatra (1968) and Turner and Patrick (1968).

Two staining tests were performed: (a) a 0.2-percent α, α' -dipyridyl solution in 10-percent acetic (Bouma 1989), and (b) a 0.2-percent α, α' -dipyridyl solution buffered with 1 M ammonium acetate (Childs 1981). The dye was dropped onto freshly broken surfaces of field samples taken at 0.25-, 0.50-, and 1.00-m depths. A positive reaction indicating the presence of reduced iron was obtained when a strong pink color developed almost immediately.

Table 2
Soil Series, Location by Parish, Geological Unit, Land Resource Region, and Land Use

Soil Series	Parish	Geological Unit	LRR/MLRA ¹	Land Use
Commerce	Iberville	Holocene	O/131	Meadow
Sharkey	Iberville	Holocene	O/131	Meadow
Fausse	West Baton Rouge	Holocene	O/131	Bottomland Hardwoods
Verdun	Livingston	Pleistocene	P/134	Pine, Pulpwood
Crowley	Acadia	Pleistocene	T/150A	Cropland, Rice, and Soybeans
Lebeau	St. Landry	Pleistocene	O/131	Cropland, Rice, and Crawfish
Moreland	Rapides	Pleistocene	O/131	Pasture and Cropland
Beauregard	Beauregard	Pleistocene	T/152B	CRP
Brimstone	Calcasieu	Pleistocene	T/150A	Cropland, Rice, Wheat, Soybeans, and Crawfish

¹LRR = Land Resource Region, MLRA = Major Land Resource Area. O = Mississippi Delta cotton and feed grains region; P = South Atlantic and Gulf Slope cash crops, forest, and livestock region; T = Atlantic and Gulf Coast Lowland forest and crop region. 131 = Southern Mississippi Valley Alluvium, 134 = Southern Mississippi Valley Silty Uplands, 150A = Gulf Coast Prairies, 152B = Western Gulf Coast Flatwoods.

Water from each piezometer was pumped out, and the pH of the water samples was measured immediately with a pH meter. The pH of the water was considered to be the soil pH, assuming near equilibrium between the soil solution and the solid phase (Breemen and Brinkman 1978). Soil temperature was measured at a 0.50- and 1.00-m depth from samples taken with a push probe and measured immediately in the field with a stem thermometer.

Soil morphology was obtained through a detailed description of each horizon from exposed profiles at the time the soil was sampled for detailed chemical, physical, and mineralogical characterization. Profile descriptions were used to test regional hydric soil field indicators.

Results

Commerce soil

Soil characteristics. This nearly level loamy soil is on the high parts of the natural levees of the Mississippi River and its distributaries. It formed in loamy alluvium. Slope gradients are less than 1 percent. Typically, the surface layer is dark grayish brown silt loam about 38 cm thick. The subsoil to a depth of 116 cm is grayish brown silt loam with redoximorphic features in shades of brown. The underlying material is silty clay loam and silty clay with dark brown redoximorphic features.

Saturation. Rainfall and water table data from the 2-m piezometers are presented in Figure 2. The water table tracked the rainfall distribution during 1989, but not during 1990. This site was close to the Mississippi River, and the lower sandy units of this profile were hydrologically connected to the river. The river stage for 1989 was low because of unusually low rainfall. During 1989, the water table responded to rainfall.

During 1990, the river stage was high during February and March. Rainfall was normal during January, and the soil was saturated during these months (see tensiometer data, Figure 3). During April, as the river stage began to fall, the water table also began a steady drop. The soil began to drain of free water in response to the lowering water table (Figure 2).

Tensiometer data (Figure 3) showed that the soil was saturated above 50 cm for 52 percent of the observations, and it was above 100 cm for 85 percent of the observations (Table 3). These data support endoaquic saturation.

Reduction. Observed groundwater depths matched the Eh measurements of Figure 4. pH-corrected Eh thresholds (Patrick and Mahapatra 1968; Turner and Patrick 1968; Patrick 1980) for Commerce soil were moderately reduced below 314 mV, reduced below 164 mV, and highly reduced below -136 mV. Figure 4 shows that most of the time redox potentials at 100-cm depth were in the reduced (< 164 mV) and moderately reduced (< 314 mV)

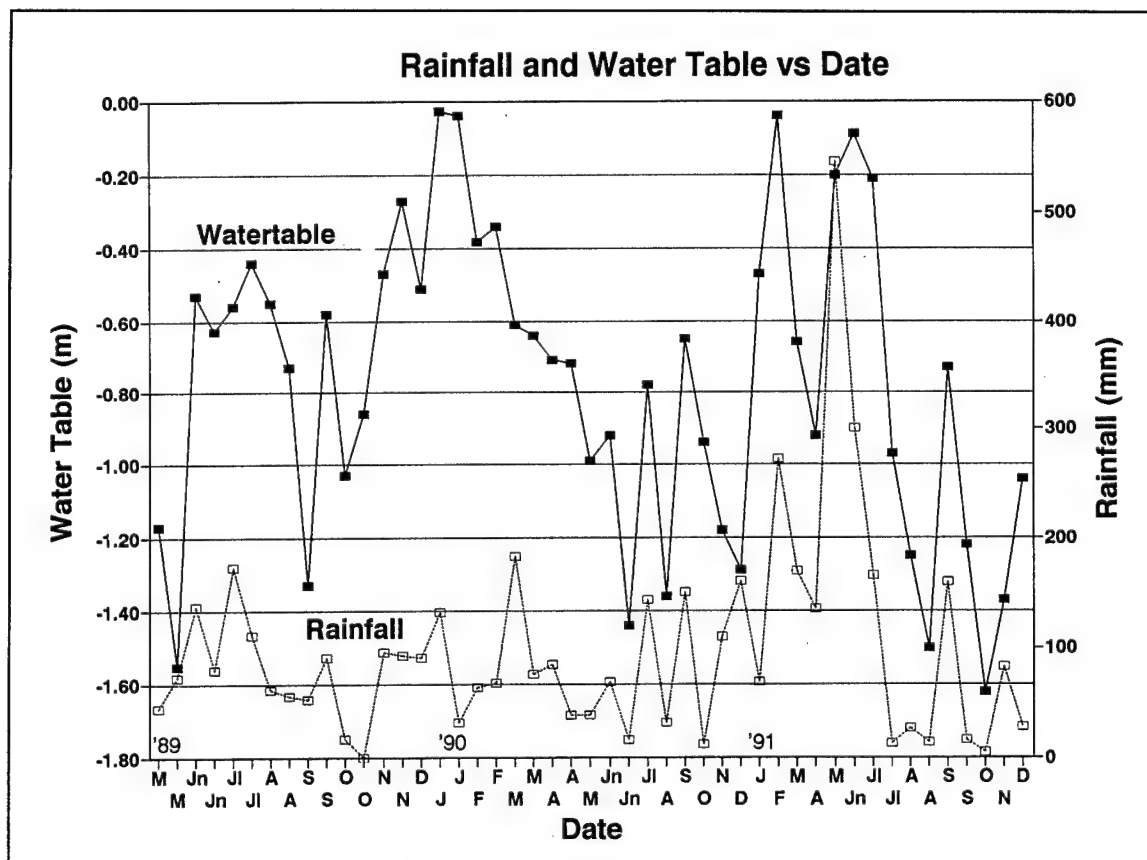


Figure 2. Rainfall and water table data for Commerce silt loam

ranges. Redox potentials at 50-cm depth fluctuated among the four ranges (oxidized, moderately reduced, reduced, and highly reduced) following the changes in water table depth and saturation. Some of the more intense changes in reduction at 50 cm are explained by the presence of organic matter (percent carbon was higher in the upper horizons), absence of oxygen supply due to the rising water table, and the presence of anaerobic organisms.

The reduction tested with α, α' -dipyridyl was better correlated with water table fluctuations at 50 and 100 cm than at 25 cm. The number of observations with positive dye reaction was much higher than the number of observations of saturation at 25 cm. This fact can be explained by the following: (a) the long equilibration time of the tensiometers could not account for rapid changes of soil moisture in the first 25 cm, and (b) the soil was reduced at microsites when it was wet but not saturated. The situation was reversed at 100 cm. The percentage of observations with saturation was higher than the percentage with positive dye reaction.

The influence of the river stage was also displayed in the Eh data. During most of 1989, the water table was a function of rainfall. As the water moved downward, O_2 was depleted, and the Eh at 50 cm dropped below -100 mV

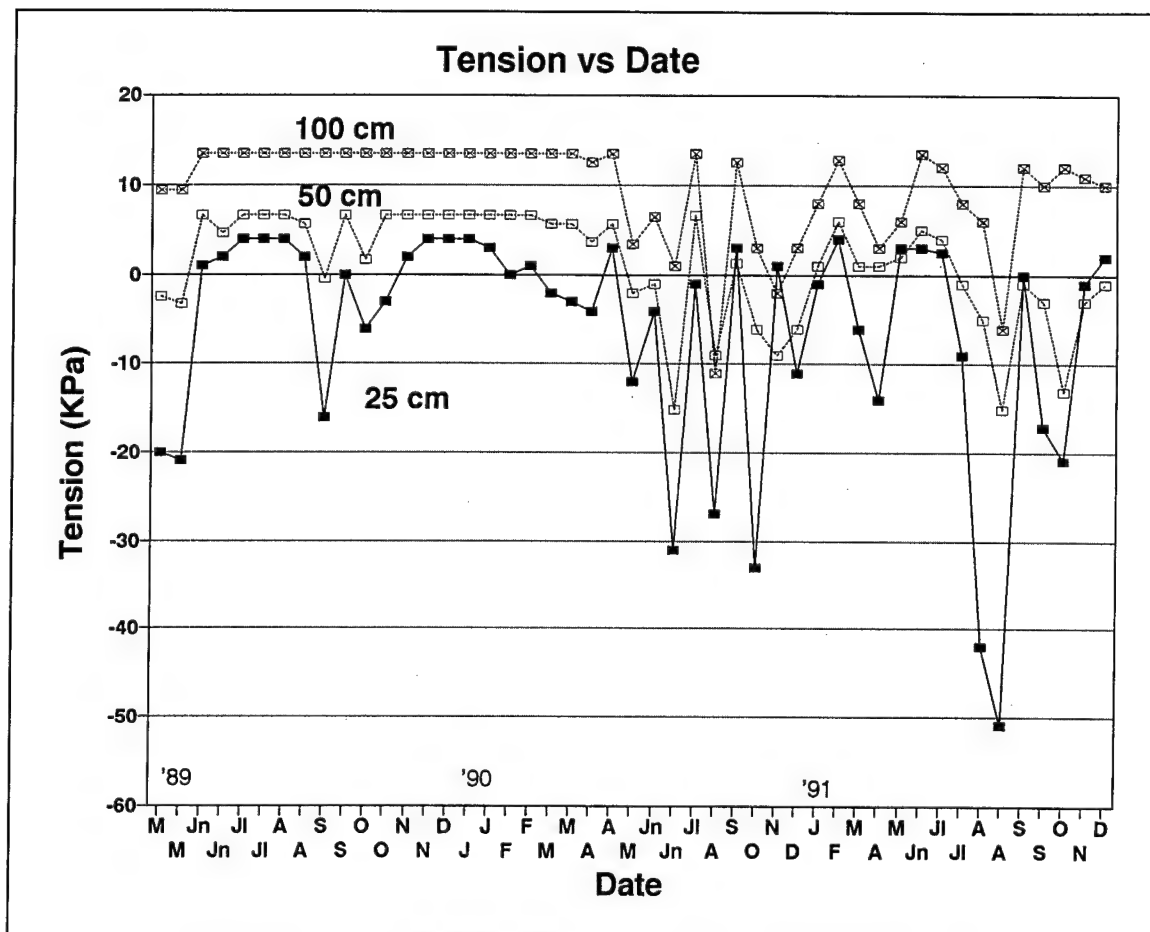


Figure 3. Tensiometric data from 25, 50, and 100 cm for Commerce silt loam

Table 3
Percentage of Observations With Reduced Conditions, Saturation, and/or Water Tables Above Selected Depths in Commerce Silt Loam

Condition	Depth, cm		
	25	50	100
Reduced ¹	52.0	64.0	80.0
Saturated ²	26.0	51.9	85.2
Piezometer ³	8.3	29.2	83.3
Borehole ⁴	8.3	31.0	79.2

¹ Positive reaction to α, α' -dipyridyl.

² Zero or positive tension.

³ Free water in piezometer above a given depth.

⁴ Free water in the borehole above a given depth.

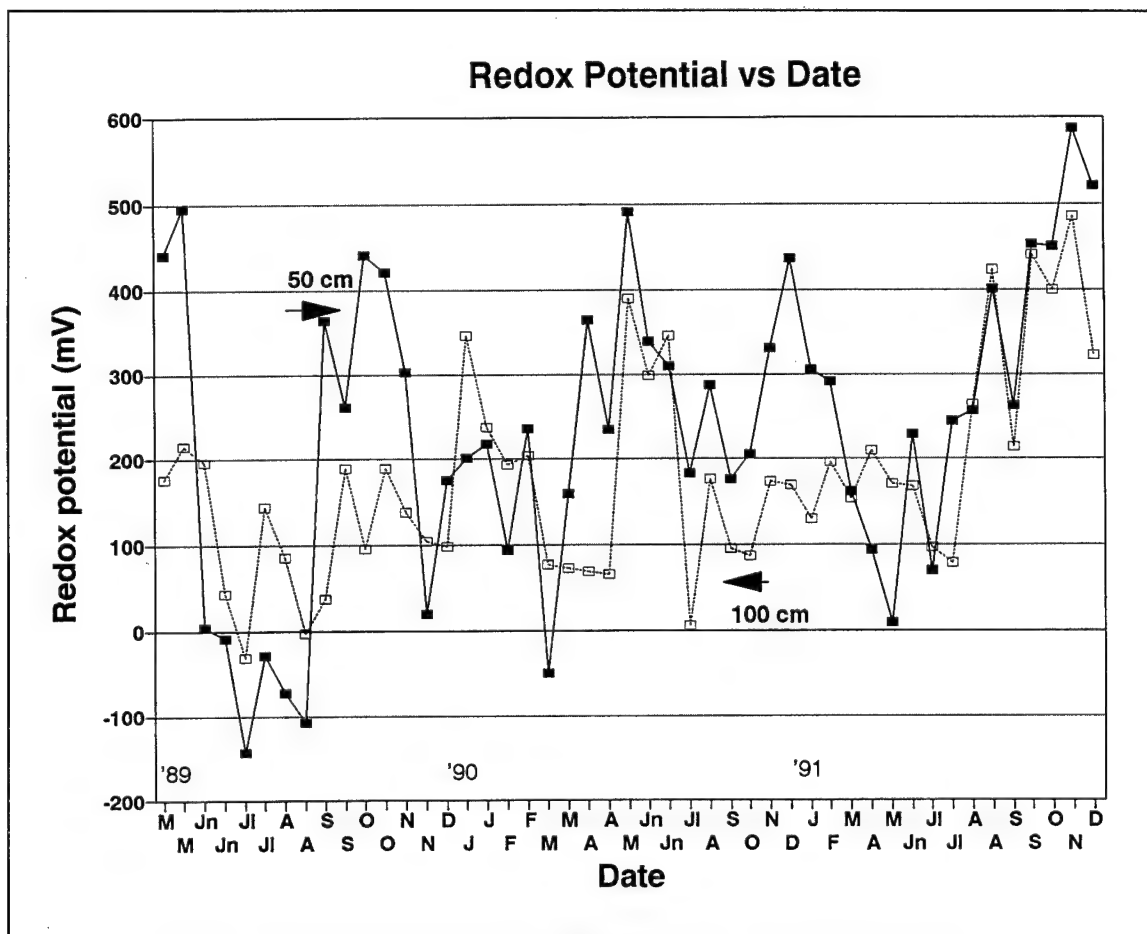


Figure 4. Redox potential data from 50 and 100 cm for Commerce silt loam

during periods of peak of rainfall. However, during late 1989 and 1990 when the water table was being controlled by the river stage, Ehs were higher. The belief is that water flowing laterally from the river was oxygenated. Since there was little or no energy nor microbes in these hydrological layers, the water remained oxygenated.

Redoximorphic features. In the upper 50-cm zone (Ap1, Ap2, and Bw1 horizons) of the Commerce soil, macromorphic features included dominant matrix colors of 4/2 and 5/2 with few to common iron stains in root channels and on vertical and horizontal ped faces. In the 50- to 100-cm zone (Bw2 and Bg1 horizons), macromorphic features included dominant matrix colors of 5/2 with common iron and manganese segregation. In the 100- to 200-cm zone (Bg2, Bg3, and Bssgb horizons), macromorphic features included dominant matrix colors of 5/1 with common 4/3 and 4/4 iron-manganese segregations.

Hydric soil characteristics. The ponded phase of the Commerce is on the hydric soils list, but all other Commerce soils are not hydric. The critical depth for this Entisol is 40 to 50 cm. This pedon met the criteria for aquic conditions within that depth and is therefore placed into the Aquepts. The

Commerce soils are somewhat poorly drained. The hydric criteria require that the somewhat poorly drained soils have a frequently occurring water table within 15 cm of the surface for a period of at least 2 weeks during the growing season. There are some Commerce soils that, if hydric soil indicators are used (value 4 and 5, chroma 1 and 2), would be hydric (Indicator F3, Depleted Matrix, Natural Resources Conservation Service Staff 1995). Commerce is a borderline soil which in some landscapes is sufficiently wet and reduced to be hydric, and in others is higher on the landscape and/or is drained and is not hydric.

Sharkey soil

Soil characteristics. This level, clayey soil is at the lower parts of the natural levees of the Mississippi River and its distributaries. Slope gradients are less than 1 percent. Typically, the surface layer is dark grayish brown clay about 30 cm thick with yellowish brown redox concentrations. The next layers, extending to a depth of 212 cm, are gray and greenish gray clay with redox concentrations in shades of brown.

Saturation. Water tables were very similar to those of the Commerce soil, except that they were higher during 1989. The water table was controlled by rainfall during 1989 but was controlled by the river stage during 1990. This site was lower than the river. The well located a few meters from this site was an artesian well when the river stage was high. Tensiometer data closely resembled the borehole data. Saturation at 25 cm fluctuated in response to the changing water table. Table 4 shows that even though there was an observed water table 30.4 percent of the time at 25 cm, the soil was saturated 65.4 percent. This soil is very fine and these data reflect the capillary rise.

Reduction. Eh data and reduction with α, α' -dipyridyl (Table 4) were in close agreement. There was sufficient organic carbon. A positive reaction was expected with α, α' -dipyridyl most of the time. The only time that it was not was during the dry spring of 1989. During most of the monitoring period, the Eh at both 50 and 100 cm was less than 150 mV, or below that necessary for iron to reduce. When rainfall occurred after a brief dry period, reduction at both 50 and 100 cm was very intense.

Redoximorphic features. In the upper 50-cm zone (Ap, A, and Bss1 horizons), macromorphic features included dominant matrix colors of 10YR 4/2 and 4/1 with 4/4 iron stains and common, distinct 10YR 4/4 redoximorphic concentrations as soft masses and pore linings. In the zone between 100 and 200 cm (Bssg1, Bssg2, and BCg horizons), macromorphic features included dominant matrix colors of 5GY 5/1 with common, distinct 5/6 redox concentrations.

Hydric soil characteristics. All Sharkey soils are considered to be hydric. The sampled soil was saturated to the surface during the majority of the

Table 4
Percentage of Observations With Reduced Conditions, Saturation,
and/or Water Tables Above Selected Depths in Sharkey Clay

Condition	Depth, cm		
	25	50	100
Reduced ¹	95.5	95.5	100
Saturated ²	65.4	76.9	84.6
Piezometer ³	50.0	72.7	95.5
Borehole ⁴	30.4	60.1	91.3
¹ Positive reaction to α, α' -dipyridyl. ² Zero or positive tension. ³ Free water in piezometer above a given depth. ⁴ Free water in the borehole above a given depth.			

monitoring period. Because Sharkey is poorly drained and permeability is < 15 cm/hr, it meets hydric criteria by having a water table within 45 cm of the soil surface for at least 14 consecutive days. The soil also had a 10-cm layer within the upper 30 cm that had values and chromas within the range for the Depleted Ochric Horizon field indicator (F11).

Verdun soil

Soil characteristics. Verdun silt loam soils are level, somewhat poorly drained, and contain high levels of sodium within the subsoil. They are on broad flats on the terrace uplands. The soils are subject to rare flooding. Slopes are less than 1 percent.

Verdun soil has a surface layer of dark grayish brown, strongly acid silt loam about 10 cm thick. The subsurface layer is light brownish gray, medium acid silt loam about 20 cm thick. The subsoil to a depth of about 175 cm is grayish brown, moderately alkaline silty clay loam in the upper part, and yellowish brown, strongly alkaline silt loam in the lower part.

Saturation. Water table depths were based on measurements taken from piezometers only. The unlined borehole was affected by "bypass flow." The perched water table was difficult to follow. It occurred during summer, fall, and spring for very short periods (less than 2 weeks). It was rapidly depleted by the consumptive use of the vegetation. The pine trees also made use of the deeper ground water table. Matric potentials at 25 and 50 cm fluctuated with wetting and drying cycles within the top soil horizons (0- to 70-cm depth) during spring, summer, and fall in 1989. During the winter of 1990, the entire profile was saturated due to excess rainfall and low evapotranspiration rates. Therefore, the two water tables merged at that time. A perched water

table occurred only when the rainfall was uniformly distributed and was greater than 75 mm.

Reduction. The interpretation of Eh measurements was difficult for this soil since at 50 cm the pH was 4.7 and at 100 cm the pH was near neutrality (6.5 to 7). The pH tended to change toward the neutral point after flooding. The pH of water samples averaged 7.4 (C.V. = 6.1) and never fell below 6.6 at any depth. The Eh measured at 50 cm must be evaluated according to changes in pH. When the soil was dry the pH was near 4.7, changing to near neutrality when the soil was saturated. These two situations were governed by the occurrence of the perched water table. The Eh at 50 cm was in the oxidizing to moderately reduced range during the few dry periods when suction was > 100 kPa. Upon saturation the soil was reduced and a positive staining test was obtained (Table 5). The Eh was low enough to allow for the reduction of iron only when there was a perched water table.

Table 5
Percentage of Observations With Reduced Conditions, Saturation, and/or Water Tables Above Selected Depths in Verdun Silt Loam

Condition	Depth, cm		
	25	50	100
Reduced ¹	43.5	43.5	86.9
Saturated ²	41.7	45.8	56.0
Piezometer ³	38.1	33.3	61.9
Borehole ⁴	42.9	47.6	66.7

¹ Positive reaction to α, α' -dipyridyl.
² Zero or positive tension.
³ Free water in piezometer above a given depth.
⁴ Free water in the borehole above a given depth.

Redoximorphic features. In the upper 50-cm zone (Ap, E1, and E2 horizons), macromorphic features included dominant matrix colors of 5/2 and 7/2 with few, fine iron-manganese concretions. In the 50- to 100-cm zone (E/Bt and Btn/E horizons), macromorphic features included 6/2 matrix with 6/2 material in the tongues. There were common fine and medium 2/1 iron-manganese masses and discontinuous 2/1 iron-manganese stains. In the 100- to 200-cm zone (Btkn1, Btkn2, and Btn1 horizons), macromorphic features included areas of 6/2 colors, 2/1 iron-manganese stains and masses, and few irregularly shaped carbonate segregations and masses.

Hydric soil characteristics. The Verdun soil is not hydric even though it is an Aqualf. Verdun is somewhat poorly drained, and the data show that the soil never had a water table within 15 cm of the soil surface for at least 2 consecutive weeks during the growing season. If the hydric soil indicators are applied, this soil is nonhydric because the thick E horizon lacks common or

many distinct or prominent redox concentrations as soft masses or pore linings.

Lebeau

Soil characteristics. Lebeau clay, occasionally flooded soils are level, poorly drained, clayey soils of back swamps and the lowest parts of natural levees of old distributary channels of the Red River. It is subject to flooding for brief to long periods. Slopes are less than 1 percent. Typically, the surface layer is dark brown, mildly alkaline clay about 15 cm thick. The subsoil is dark reddish brown, mottled, moderately alkaline clay.

Saturation. This site was instrumented in January 1990. The site was in a rice-crawfish-rice management system. When the soil dries, large quantities of water are required to reflood it because of extensive cracking. The owner very rarely drains the soil for more than 2 to 3 weeks twice each year. The soil had been saturated to a depth of 1 m after flooding in February 1990. The field was drained in May for plowing and seed bed preparation. During this time, the soil became slightly dry and extensively cracked.

The Lebeau soil when managed this way wets from the top down. This was reflected in the 200-cm piezometer data of June and July. The cracks are believed to close from the surface downward. The cracks serve as water conduits to lower depths. Hydraulic conductivity is so slow that little water moves through the matrix. The water level in piezometers reflects the hydrostatic head in the cracks that are intercepted by the piezometers. This soil was never saturated below 75 cm.

Water table levels tracked the rainfall data. The water table dropped below 2 m during May while the field was drained. The high level within the 200-cm piezometer was a response to open cracks.

Reduction. When the soil had been flooded for several weeks, a reaction with α, α' -dipyridyl was observed within the top 25 cm. When the soil was drained and allowed to dry, a positive reaction was observed at a deeper depth a few days immediately after reflooding. This phenomenon was observed for nearly all the soils studied.

Platinum electrodes have been installed since July 1990, and Eh values have never dropped below 100 mv. Hydraulic conductivity is essentially zero, except along slickensides. Even though the soil may be anaerobic, there is no soluble carbon to furnish energy to the microbes, thus no Fe reduction. Also, the dominant iron mineral is hematite, which requires more energy to break the Fe-O bonds. No positive reaction with α, α' -dipyridyl was expected below 100 cm. The pH of the soil was near neutral with free CaCO_3 and gypsum. Eh must be below 150 mV for iron to reduce. The belief is that this soil is reduced, but one cannot demonstrate reduction with α, α' -dipyridyl.

Redoximorphic features. In the 0- to 50-cm zone (Ap, Bw, and Bkss horizons), macromorphic features included 4/2 matrix color in the surface with 4/4 mottles and black iron-manganese stains, and 4/2 and 5/1 redox depletions in the Bw and Bkss horizons with 5/8 and 4/1 iron stains in root channels and pores. In the 50- to 100-cm zone (Bkss and Bkssb horizons), macromorphic features included 5/1 and 4/1 iron concentrations in the upper portion.

Hydric soil characteristics. This soil was difficult to classify as hydric using either the hydric soil criteria or field indicators. The Lebeau soil is formed from Permian-aged sediments deposited in back swamps of the older distributaries of the Red River. The sediments are calcareous and may contain appreciable quantities of gypsum. When managed under rice cultivation, it is possible to mix the upper 20 cm and incorporate organic matter that is moved via the cracks to lower portions of the profile. In a few pedons, redoximorphic features are noted (10YR 5/2 depletions), but these are not present unless the soil has been cultivated. Is the alteration by man to be used to satisfy hydric criteria? This situation has not been addressed.

Lebeau is on the hydric soils list. Two criteria are used to place it there: criterion 4 (soils that are frequently flooded for long or very long duration during the growing season) and criteria 2b3 (soils that are poorly drained with a frequently occurring water table within 45 cm of the soil surface for at least 14 days during the growing season). These soils are frequently flooded, but piezometric and tensiometric data did not support a water table within 45 cm of the soil surface, not even when they were continuously flooded for rice production.

Land Resource Region (LRR) O was not included for testing draft indicator TF3 for soils with red parent materials. This soil may qualify under natural conditions, but these conditions have not been observed in cultivated fields. Redox concentrations as pore linings have not been observed under any conditions. Soils developed within red parent materials continue to present major problems for both soil taxonomy and hydric soils.

Beauregard soil

Soil characteristics. This very gently sloping, moderately well-drained soil is on broad slightly convex upland ridges. Slopes are long and smooth. Typically, the surface layer is dark gray, strongly acid silt loam about 15 cm thick. The subsoil layer is about 15 cm thick. It is pale brown, strongly acid silt loam. The subsoil to a depth of 165 cm is yellowish brown, strongly acid silt loam in the upper part; yellowish brown, light brownish gray, and light gray strongly acid silt loam in the middle part; and light gray, strongly acid silty clay loam in the lower part. Red mottles and plinthite nodules are common in the middle and lower parts of the subsoil.

Saturation. Both the water table from the piezometers and the open borehole fluctuated in response to rainfall events. Tensiometer data show that the soil was saturated for short periods at or above 50 cm about 25 percent of the monitoring period (Table 6). The tensiometer data track the piezometer very closely. Because this soil is fine-silty, water movement through the soil is good. There was little or no lag time between the tensiometers, piezometers, and the open borehole. The water seemed to be perched on a restrictive layer at 180 cm.

Table 6
Percentage of Observations With Reduced Conditions, Saturation,
and/or Water Tables Above Selected Depths in Beauregard Silt
Loam

Condition	Depth, cm		
	25	50	100
Reduced ¹	17.4	13.0	21.7
Saturated ²	17.7	25.0	43.5
Piezometer ³	4.5	27.3	50.0
Borehole ⁴	8.7	26.1	47.8

¹ Positive reaction to α, α' -dipyridyl.
² Zero or positive tension.
³ Free water in piezometer above a given depth.
⁴ Free water in the borehole above a given depth.

Reduction. As had been observed for most of the soils in this study, when there was an intense rainfall event following a long dry period, the soil underwent extreme reduction. When the soil was dry and the water table rose slowly, the soil underwent gradual reduction, but the Eh did not become as low as in the previous situation. The pH was about 5.5 from 15 to 180 cm. Iron will reduce at an Eh of about 235 mV. A positive reaction to α, α' -dipyridyl at 25 cm was observed on 17.4 percent of the observations. The soil met criteria for aquatic conditions because of the positive reaction to the ferrous iron test during the early part of the growing season. This criterion may not be valid, however, because most seasonally wet soils will give a positive reaction to α, α' -dipyridyl during the growing season. There should be a duration requirement if this criterion is to be part of *Soil Taxonomy* (Soil Survey Staff 1990).

Redoximorphic features. For the 0- to 50-cm zone (Ap1 and Ap2 horizons and the upper portion of the Bt horizon), macromorphic features included 4/2 and 6/3 matrix colors with few to common medium iron-manganese concretions. For the 50- to 100-cm zone (Bt and Ev/Btv1 horizons), macromorphic features included 6/3 matrix in the Bt horizon, and 6/2 matrix in the Ev portion and 6/2 mottles in the Btv portion of the Ev/Btv1 horizon. There

were few iron-manganese concretions and soft masses and common coarse rounded plinthite segregations.

Hydric soil characteristics. This soil is not on the hydric soils list because it is considered to be moderately well drained. It is also not hydric by field indicators because the matrix is dominated with 3 chroma colors. However, this soil developed within Coastal Plain sediments rich in iron-containing minerals. Soils on side slopes typically have 2.5YR and 5YR colors in the subsoil. The data show that this soil was saturated and reduced for more than 14 consecutive days during the growing season within 50 cm of the soil surface. The Beauregard soil is a highly weathered soil (Ultisol). Some of the redoximorphic features may be relict. It is difficult to explain the predominance of redoximorphic features throughout the soil unless it undergoes intense periods of saturation and reduction. This soil is an excellent example of one that has aquic conditions, but is not hydric.

Brimstone soil

Soil characteristics. This soil is level and poorly drained. It is on broad flats on the terrace uplands. Slopes range from 0 to 1 percent. Typically, the surface layer is dark grayish brown, slightly acid silt loam about 15 cm thick. The subsurface layer is grayish brown, slightly acid silt loam about 30 cm thick. The subsoil extends to a depth of about 175 cm. It is light brownish gray and grayish brown, mottled, neutral silt loam in the upper part; grayish brown, mottled, mildly alkaline silty clay loam in the middle part; and light olive gray, mottled, moderately alkaline silty clay loam in the lower part.

Saturation. The Brimstone soil was saturated approximately 30 percent of the time within the upper 25 cm, 26 percent above 50 cm, and 39 percent above 100 cm (Table 7). The water table responded to rainfall events. There were periods when the upper 50 cm was saturated with dry layers below. The soil wets from the top downward with very little lag time between the 25- and 50-cm depths. There was a lag at the 100-cm depth, which is within the natric (Btng1) horizon.

Reduction. There was a positive α, α' -dipyridyl reaction 64 percent of the time at 25 cm, 41 percent at 50 cm, and 36 percent at 100 cm (Table 7). This soil was unique in that a positive dry reaction was obtained more often than the soil was saturated. The Eh data show that the soil is one of extremes. It was not uncommon for the soil to drop several millivolts when the soil was saturated for a short time. The upper 50 cm were always more reduced than at 100 cm. This may be due to the exchangeable sodium and/or the soluble chloride and sulfate anions. The pH of the upper 50 cm was moderately acid to neutral. Under saturated conditions, it was likely to be moderately acid (pH = 5.5) and iron would reduce at an Eh of about 235 mV. The soil was moderately alkaline (pH = 7.8) at 100 cm, and a Eh of about 85 or less would be required for iron reduction. Eh values were

Table 7

Percentage of Observations With Reduced Conditions, Saturation, and/or Water Tables Above Selected Depths in Brimstone Silt Loam

Condition	Depth, cm		
	25	50	100
Reduced ¹	63.6	40.9	36.4
Saturated ²	30.4	26.1	39.1
Piezometer ³	18.2	31.8	31.8
Borehole ⁴	27.3	31.8	40.9

¹ Positive reaction to α, α' -dipyridyl.
² Zero or positive tension.
³ Free water in piezometer above a given depth.
⁴ Free water in the borehole above a given depth.

never that low at 100 cm, and yet a positive dye reaction was obtained. The dye was prepared in 10-percent acetic acid, and the dye itself lowered the pH to allow the positive test. An α, α' -dipyridyl solution prepared in 1 N neutral (pH = 7) NH_4OAc is now used, and results more consistent with the Pt electrodes are being obtained.

Redoximorphic features. For the 0- to 50-cm zone (Ap, Eg, and E/Btng horizons), macromorphic features included 5/3 matrix color, few fine 7/2 silt pockets and 6/8 iron stains in root channels and pores (Ap horizon); 6/2 matrix with 4/6 iron stains (Lepidocrocite) in the Eg horizon; and 6/2 matrix with many 7/1 silt pockets, 4/6 ferritans (Lepidocrocite) and patchy manganese or iron-manganese stains on vertical faces of peds. In the 50- to 100-cm zone (Btng/E and Btng1 horizon), macromorphic features included 6/2 matrix, 4/2 continuous clay films, and few medium rounded soft masses of iron-manganese. There were few 7/1 and 7/2 silt pockets.

Hydric soil characteristics. The Brimstone soil is poorly drained and is on the hydric soils list. The natric horizon restricts drainage, and the soil was saturated and reduced with redoximorphic features within 25 cm of the soil surface. The perched water table was within 45 cm of the soil surface. There was little doubt that this soil was hydric. The soil had a preponderance of crawfish krotovinas throughout the upper 1 m. These burrows restricted water movement and may be more restrictive than the natric properties. The soil qualified as hydric under hydric soil indicator F3, Depleted Matrix. There was a proposed testing of soils with natric horizons in LLR D. This soil was located in LLR T, but it was tested against the proposed indicator. It failed because the upper boundary of the natric horizon was deeper than 30 cm.

Acknowledgments

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References

- Bouma, J. (1989). ICOMAQ Circular Letter No. 9, Wageningen Agricultural University, Wageningen, The Netherlands.
- Breemen, N. van, and Brinkman, R. (1978). "Chemical equilibria and soil formation." *Soil chemistry. A. Basic elements*. G. H. Bolt and M. G. M. Bruggenwert, ed., Elsevier Scientific Publishing Co., Amsterdam, The Netherlands, 141-170.
- Childs, C. W. (1981). "Field test for ferrous iron and ferric-organic complexes (on exchange sites or in water-soluble forms) in soils," *Aust. J. Soil Res.* 19, 175-180.
- Jones, R. H. (1966). "Oxidation-reduction potential measurements," *ISA J.* 13, 41-44.
- Natural Resources Conservation Service Staff. (1995). "Field indicators of hydric soils in the United States," USDA-NRCS Ver. 2, Washington, DC.
- Patrick, W. H., Jr. (1980). "The role of inorganic redox systems in controlling reduction in paddy soils." *Symposium on paddy soils, Proc. Institute of Soils Science, Academia Sinica*. Anonymous, ed., Nanjing, China, 107-117.
- Patrick, W. H., Jr., and Mahapatra, I. C. (1968). "Transformation and availability to rice of nitrogen and phosphorus in waterlogged soils," *Adv. Agron.* 20, 323-359.
- Reeve, R. C. (1986). "Water potential: Piezometry." *Methods of soil analysis*. Part 1. 2nd ed. *Agro. Mon.* 9, 545-561. Soil Sci. Soc. Am., Madison, WI.

Soil Survey Staff. (1975). *Soil taxonomy: A basic system of soil classification for making and interpreting soil surveys*. USDA Soil Conservation Service, Agricultural Handbook. No. 436, U.S. Government Printing Office, Washington, DC.

_____. (1990). *Keys to soil taxonomy*. SMSS Technical Monograph No. 19, AID-USDA-SMSS, 4th ed., Virginia Polytechnical Institute and State University, Blacksburg, VA.

Szögi, A. A., and Hudnall, W. H. (1992). "Classification of soils in Louisiana according to "Endoaquic" and "Epiaquic" concepts." *Proceedings of the eighth international soil correlation meeting (VIII ISCOM): Characterization, classification and utilization of wet soils*. J. M. Kimble, ed., USDA, NRCS, National Soil Survey Center, Lincoln, NE, 271-278.

Turner, F. T., and Patrick, W. H., Jr. (1968). "Chemical changes in waterlogged soils as a result of oxygen depletion." *Trans. Int. Congr. Soil Sci.*, 9th, 1968. Adelaide, Australia, 53-56.

4 Soil Moisture Regimes of Some Toposequences in Indiana¹

Introduction

Three toposequences that represent large areas in Indiana and nearby States were studied. In two toposequences, the wettest soils are in the highest part of the landscape and in one they are in the lowest part of the landscape. In the two in which the wet soils are high in the landscape, the pattern of poorly and somewhat poorly drained soils differs. At Muscatatuck, on the Illinoian till plain, the poorly drained soils occupy large interior areas of the flat summits. They are surrounded by a band of somewhat poorly drained soils near the edge of the flats. Downslope, on the beveled edge of the till plain around the drainageways, are the moderately well-drained soils on the upper shoulder positions and the well-drained soils on the lower shoulders and backslopes.

In Moore's Woods, on the Wisconsin till plain, the wetter soils are also high in the landscape, but here the pattern of poorly and somewhat poorly drained soils is more random, like the spots on a Dalmatian dog. Similar to the Illinoian sequence, the better drained soils are on the till plain bevel. This pattern represents much of the Wisconsin till plain in the lake States. In contrast, at the Shades State Park site, the wettest soil is low in the landscape, on toe slopes. This pattern is typical of end moraines and, in this case, highly dissected till plains. This toposequence is also of Wisconsin age.

The objectives of this study are to characterize the seasonal water levels in soil landscapes, to characterize properties related to water levels such as redox potential, to relate these characteristics to soil morphological features, and to deduce how water moves through the landscape.

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Methods

The methods used to develop the information base were patterned after the field study of wet soils organized by the Soil Management Support Services of the Natural Resources Conservation Service and conducted in Louisiana (Hudnall and Wilding 1992). Depth to the free-water surface was measured using a single observation well. Hydrostatic water pressures were measured at 25-, 50-, 100-, 200-, and 450- or 475-cm depths using a nest of piezometers. Three replications were installed at each depth except the 450-/475-cm piezometer. A single piezometer was installed at this depth. Temperatures were measured at various depths using thermocouple devices. Two replications at 25, 50, 100, and 200 cm were installed. Oxidation/reduction potentials were measured using platinum electrodes. Three replications were installed at 25, 50, and 100 cm. The Fe(III)-Fe(II) boundary represents the thermodynamically stable fields at the average pH of the soil (McBride 1994, Figure 7.9). This theoretical potential is higher than ranges of soil potential over which these Fe species react (McBride 1994, Figure 7.5).

Muscatatuck Toposequence

Soils

Four sites at Muscatatuck Wildlife Refuge were monitored for water table levels, oxidation/reduction potential, temperature, and matric potential. The sites are located on a Clermont-Cincinnati toposequence of soils on the Illinoian till plain of southern Indiana in Township 6N, Range 7E, the NW¼ of Section 19 in Jennings County. The sequence of soil parent materials from the surface is silty Wisconsinan loess, "gritty" Wisconsinan loess, a loamy zone, and the major Sangamon paleosol. The loamy zone is not always present. Fragipans form mainly in the gritty loess, but parts of them are also in the silty loess and the loamy zone. The range of elevations for these sites is from 173 to 178 m.

This soil association makes up extensive portions of Jennings county and much of the area of surrounding counties in both southeastern Indiana and southwestern Ohio. The landscape is one of large level summits dissected by drainageways. The drainage classes of these soils grade from poorly drained interiors to well-drained backslopes (Table 1).

Piezometric head and water table level

Piezometric heads and water table depths were recorded for 1992 and 1993 using piezometer nests and an observation well at each site. Three distinct water systems were observed in the Clermont, Avonburg, and Rossmoyne soils (e.g., graph A of Figure 1 for the Clermont soil):

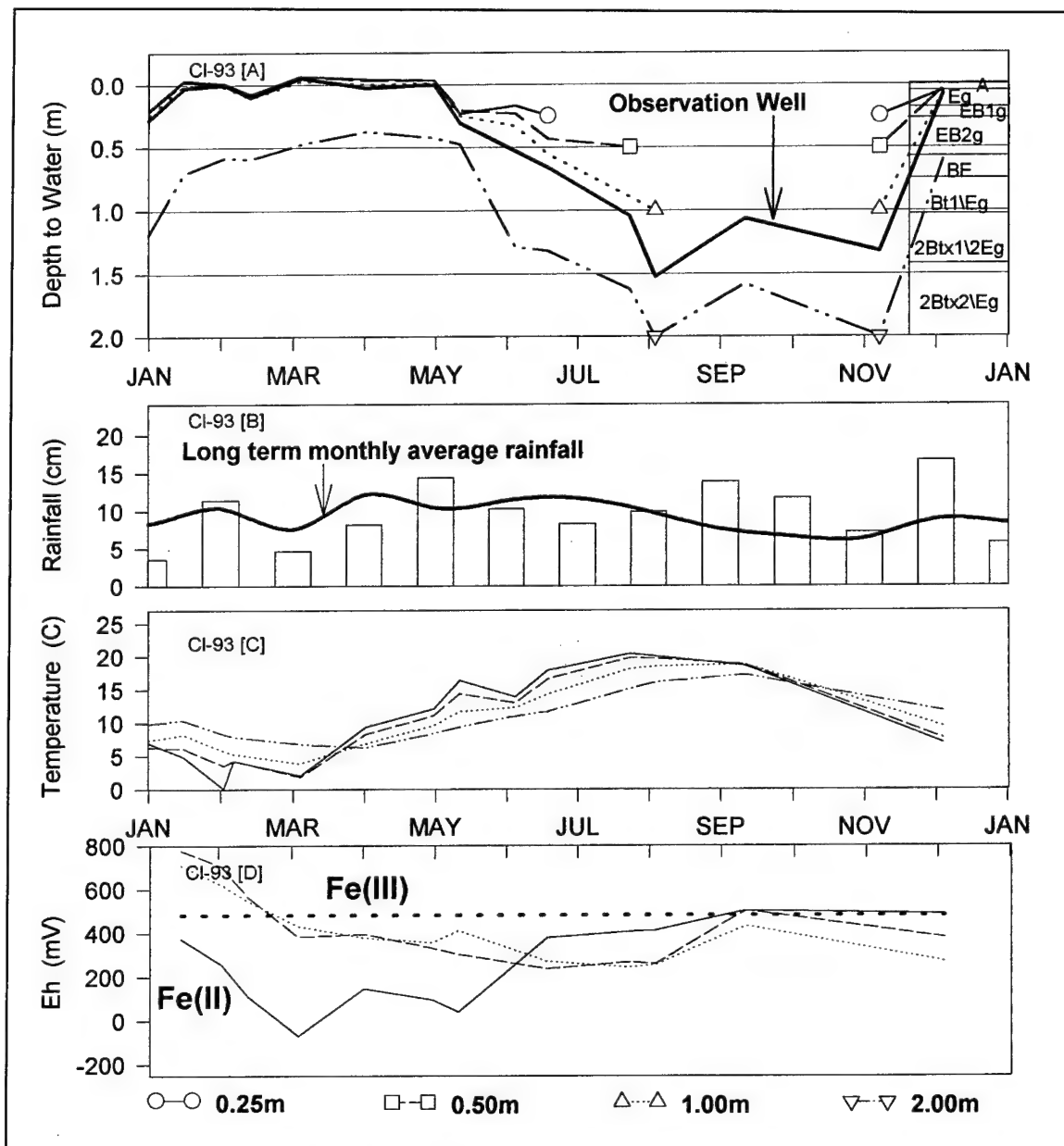


Figure 1. Clermont series data set 1993; [A] depth of water in piezometers and observation well (installed November 1992), [B] rainfall, [C] temperature, [D] redox potential (Eh). Depth of piezometers indicated by symbol and line pattern; unfilled symbols represent empty piezometers

- a. The water level in the 25-, 50-, and 100-cm piezometers was nearly the same (ψ_1). These tubes were all above the fragipans.
- b. The water level in the 200-cm piezometer (ψ_2) paralleled that in the shallower ones, but was about 50 cm lower. It terminated above the paleosol.

- c. The 475-cm piezometer, open below the main paleosol B horizon, was dry throughout the period.
- d. The water level in the observation well was similar to ψ_1 during the winter and spring and between ψ_1 and ψ_2 during the summer and fall.

In these soils, water was held up by the fragipan, but some penetrated the pan and was held up by the paleosol. Very little water penetrated the paleosol as shown by the empty piezometers at 475 cm.

The piezometric surface in the Cincinnati soil followed a different pattern. The soil at 25, 50, 100, and 200 cm was only occasionally saturated after a significant rainstorm, but the soil at 475 cm was continuously saturated. The groundwater was not held up by the fragipan or the paleosol of this soil like it was in the other soils. Apparently, the deep water level represents the regional water table level. In the Cincinnati soil at the edge of the broad summits, the fragipan and paleosol are both thinner and less developed than in the other soils. The rain that falls on these soils, and the water that moves into them as throughflow, percolates through these horizons to the regional water table.

Landscape hydrology

Figure 2 represents the piezometric surfaces in the spring. During this season, the water table level was below the upper piezometric surface and above the lower piezometric surface. In the Clermont, Avonburg, and Rossmoyne soils, water is held up by the fragipan in the spring. When the horizons above the fragipan in the three soils become saturated, a small amount of water moves downward, mostly through the large planar voids between the prisms. Most, however, moves laterally down the shallow gradient of the fragipan surface toward the dissected bevel of the till plain. The water that penetrates the pan is held up by the very slowly permeable paleosol. It saturates the soil above the paleosol, including the lower part of the fragipan, and also moves laterally toward the drainage ways. In the Cincinnati soil, water moves downward through the thinner fragipan and paleosol to the regional water table. This suggests that most recharge of the water table takes place in the dissected drainageways, not in the upland summits.

Rainfall

Rain and snow accumulation was recorded at Muscatatuck Wildlife Refuge by refuge personnel. The 97-cm yearly total for 1992 was below the historical average (1887 to 1972), while the 122-cm rainfall in 1993 (graph B of Figure 1) was somewhat higher than normal. Water table levels are assumed to be slightly below normal and of shorter duration in 1992 and normal to slightly above normal in 1993. The average annual rainfall in Jennings County is approximately 112 cm.

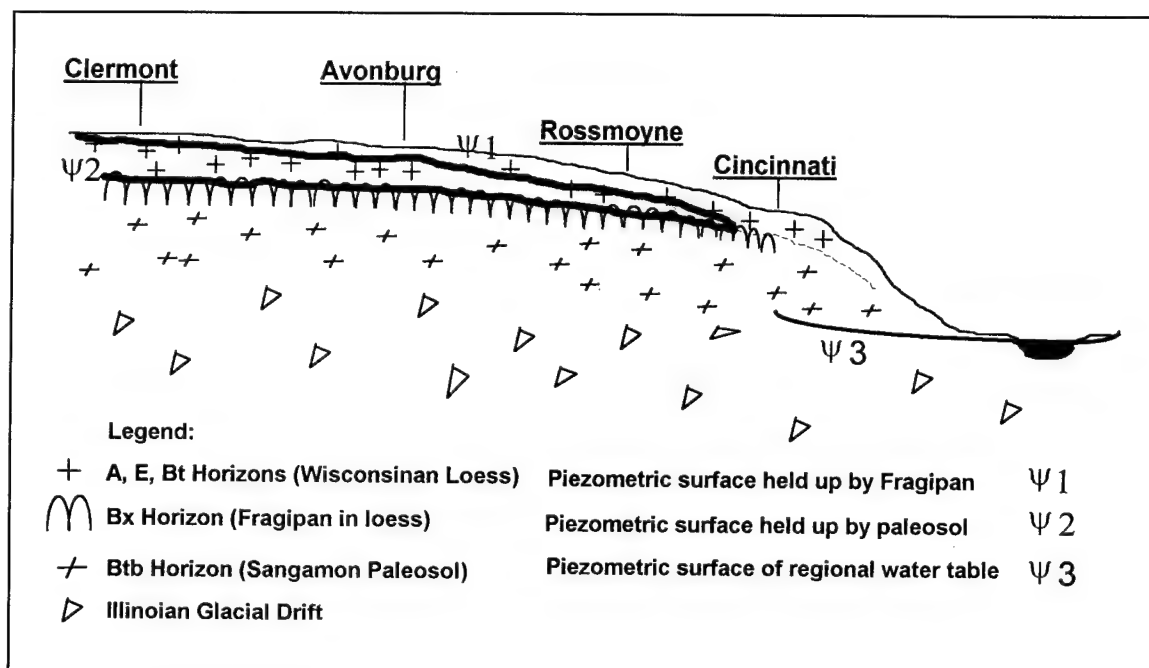


Figure 2. Cross-section sketch through landscape at Muscatatuck Wildlife Refuge showing typical piezometric surfaces in spring

Temperature

Soil temperatures (e.g., graph C of Figure 1) did not vary appreciably among sites. Seasonal crossover points, when the soil temperature was the same at all depths, occurred at the end of March and in the first part of October, respectively. Soil temperatures at 25 cm were above 5 °C from mid-March to December in 1993.

Redox measurements

Redox potential at 25-cm depth was below the thermodynamic Fe(III)-Fe(II) stability line in the spring in Avonburg. In the Clermont soil (graph D of Figure 1), redox potential was lower than in Avonburg and was below the stability line for a longer period. The average pH for the top meter of soil was 4.4 for each soil.

Comparison of water table levels among soils

Water table levels in 1993 in the Clermont, Avonburg, and Rossmoyne soils were high through the winter and spring, dropped rather sharply in the summer, and rose in the late fall. The water table level in the Cincinnati soil was more variable. It rose and fell in response to short-term precipitation patterns. Water table levels followed about the same trend in 1992 except that

they did not rise until late spring, and then they rose and fell in all soils during the summer.

In overview, the landscape interior, with Clermont, Avonburg, and Rossmoyne soils, becomes saturated by winter rain and melting snow. When extra precipitation falls on the saturated landscape, water moves periodically outward to the Cincinnati soil at the edge of the broad summit. Then the water table level rises rapidly in that soil, only to fall rapidly when the surge of water passes.

Time of saturation

Figure 3 represents the percentage of time that every horizon was saturated in both 1992 and 1993. It shows, too, that the three interior soils act similarly, but differently from the Cincinnati soil at the landscape edge. In the upper 25 cm, the percentage of time saturated follows fairly regularly the progression Cincinnati < Rossmoyne < Avonburg < Clermont. The Clermont soil is saturated at the surface much more than the other three soils.

Shades State Park Toposequence

Soils

Two sites at Shades State Park were monitored for water table levels, oxidation/reduction potential, temperature, and matric potential. The sites are located on a Russell-Reesville association of soils on the Wisconsinan till plain in west central Indiana in Township 17N, Range 6W, the NE ¼ of Section 9 in Parke County. The range of elevations for these sites is from 219 to 229 m.

This soil association makes up approximately 10 percent of Parke County. The two soils of the toposequence occur on a rolling dissected landscape. The Washtenaw soil developed on a toeslope position where colluvium covered lacustrine silts and glacial till. The well-drained Russell soil formed in 125 cm of Wisconsinan loess over calcareous Wisconsinan loam till on the summit of a small hill west of the Washtenaw site. The drainage classes of these soils grade from poorly drained soils on toeslope to well-drained soils on summits (Table 1).

Piezometric head and water table level

The nest of piezometers in the Washtenaw soil (graph A of Figure 4) tended to act as a unit showing little variation in the readings of instruments placed at different depths. This soil reflects an endosaturated condition and is the wettest soil in the study. The data recorded from the observation well in

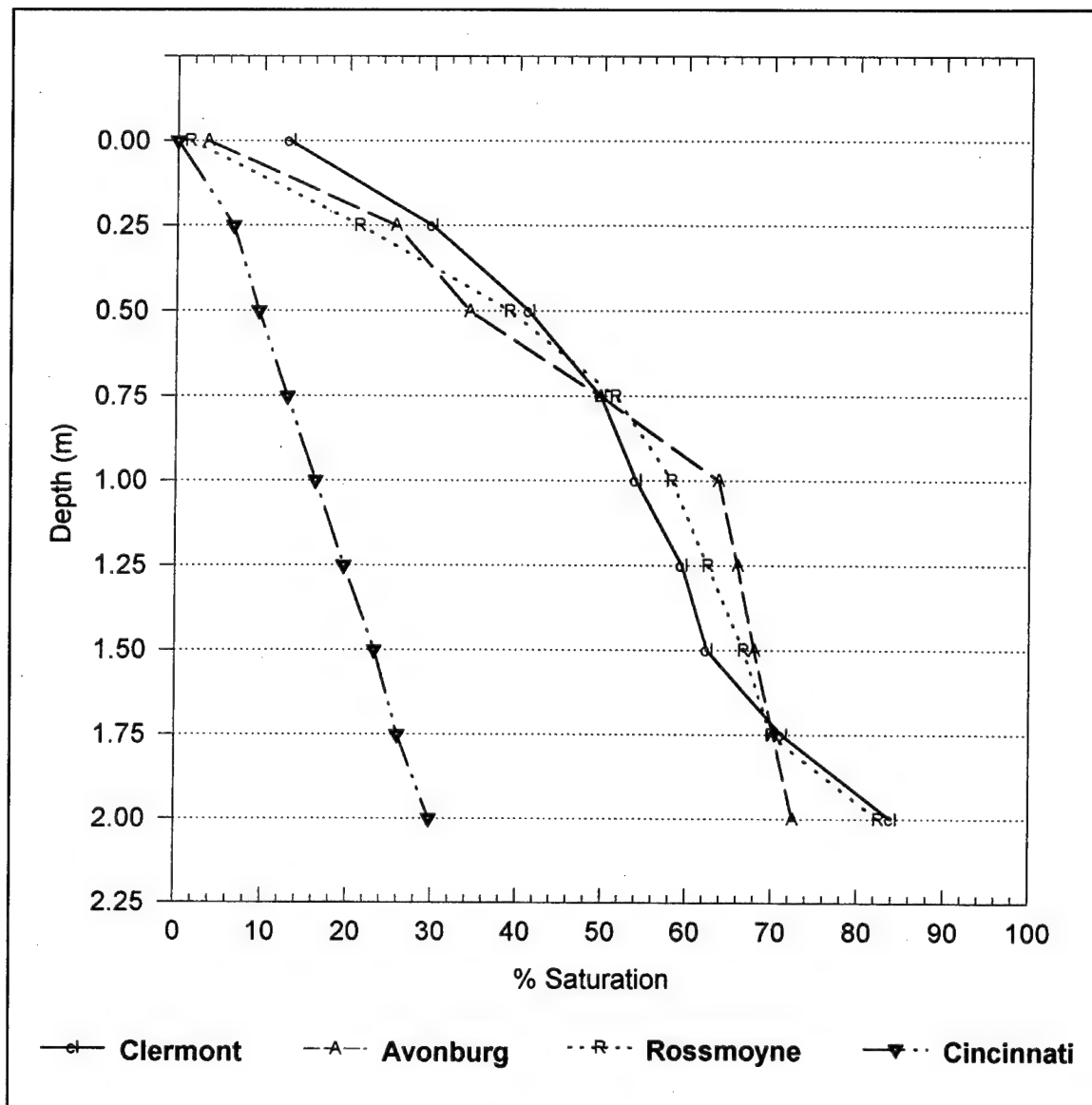


Figure 3. Relative time of saturation in Muscatatuck toposequence showing percentage of time each soil horizon was saturated down to a depth of 2 m

1993 parallels the piezometric water levels as they rise and fall. The measurements reflect the shallowest water level measured in any of the soils of this study. Saturated conditions in the Russell soil occurred only occasionally, and then for very short periods. During the winter and spring of 1993, rainfall was plentiful and a water table developed at a depth of 3 to 4 m.

Table 1 Summary of Soils in the Three Toposequences			
Soil Series	Landscape Position	Drainage Class	Classification¹
<i>Muscatatuck Toposequence</i>			
Clermont var.	Till plain interior	Poorly	Typic Fragiaqualf
Avonburg	Till plain edge	Somewhat poorly	Aeric Fragiaqualf
Rossmoyne	Shoulder of till plain bevel	Moderately well	Aquic Fragiudalf
Cincinnati	Backslope of till plain bevel	Well	Typic Fragiudalf
<i>Shades State Park Toposequence</i>			
Washtenaw	Toeslope	Poorly	Typic Ochraqualf
Russell	Summit	Well	Typic Hapludalf
<i>Moore's Woods Toposequence</i>			
Delmar	Till plain swale	Poorly	Typic Ochraqualf
Fincastle	Till plain swell	Somewhat poorly to moderately well	Aquic Hapludalf
Russell	Backslope of till plain bevel	Well	Typic Hapludalf
Ragsdale	Till plain swale	Poorly	Typic Haplaquoll
¹ All soils are in fine-silty, mixed, mesic families.			

Landscape hydrology

The landscape hydrology of these soils follows the more traditional model in that the best drained soils are in high landscape positions. Water moves from these soils to those in lower positions over the surface and as through-flow (Figure 5).

Rainfall

Rain and snow accumulation were recorded at Shades State Park by park personnel. The yearly total for 1992 was 138 cm and for 1993 was 145 cm (graph B of Figure 4). Rainfall was above the historical average (104 cm) for both years. The water table levels for these 2 years are assumed to be above normal and of longer duration than the average.

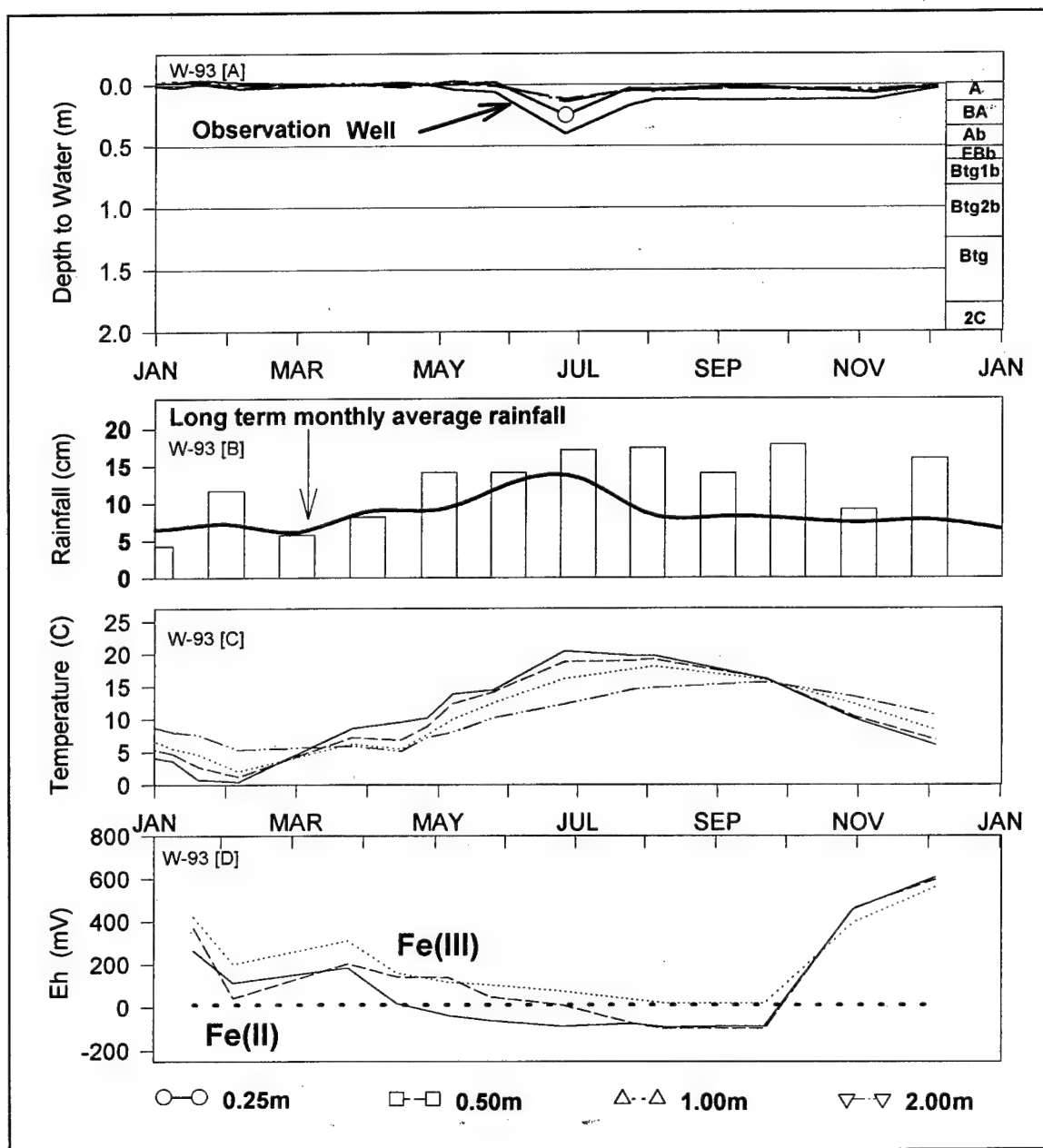


Figure 4. Washtenaw series data set 1993; [A] depth of water in piezometers and observation well (installed November 1992), [B] rainfall, [C] temperature, [D] redox potential (EH). Depth of piezometers indicated by symbol and line pattern; unfilled symbols represent empty piezometers

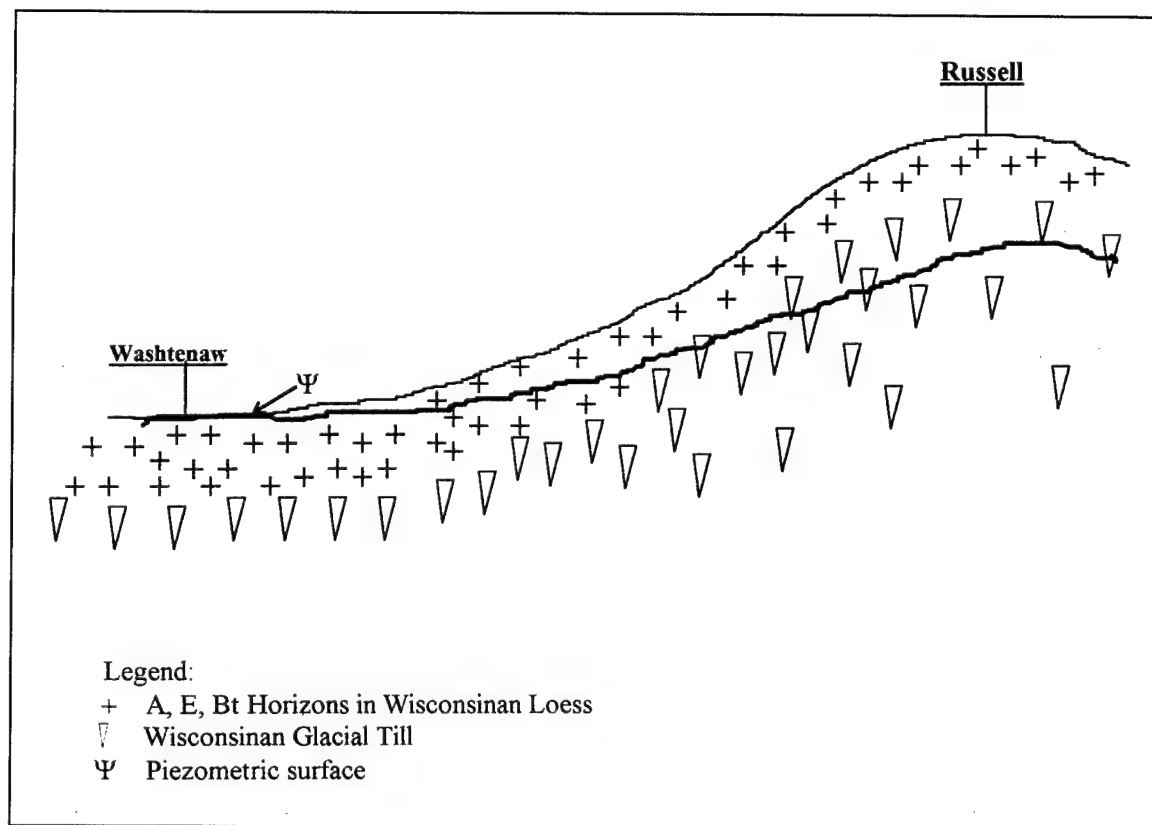


Figure 5. Cross-section sketch through landscape at Shades State Park showing typical piezometric surfaces in spring

Temperature

The seasonal pattern of temperature rise and fall for the Washtenaw soil is displayed in graph C of Figure 4. Temperature variation was high relative to other sites. The variation reflects the hydrology of the two sites; the Russell site was the driest and the Washtenaw was the wettest site in the study. The crossover points, when soil temperature was the same at all depths, occurred in March for both soils. In the fall, it occurred in September in the Washtenaw and in October in the Russell. At the 25-cm depth in both soils, temperature was above 5 °C in 1993 from early March to December.

Redox measurements

Platinum electrodes were installed at the Washtenaw site only. The soil was reduced relative to the Fe(III)-Fe(II) stability line throughout the spring, summer, and early fall of 1993 due to extended saturation near the soil surface during this time period. The average pH of the top meter of soil at this site is 6.7.

Comparison of water table levels among soils

Water table levels for this sequence of soils are typical of morainic landforms. The wettest soil is low in the landscape. Surface runoff and throughflow channel large quantities of water into these low areas from adjacent summits and slopes, and as a consequence, they stay saturated to the surface for extended periods. The summits of end moraines that are highly dissected are saturated very little. The water table stays deep in the profile. Saturation within the solum occurs only when a large rain falls.

Time of saturation

Figure 6 represents the percentage of time that every horizon was saturated in both 1992 and 1993. It shows the greatest contrast in time of saturation for the study as a whole. The poorly drained Washtenaw was saturated almost 40 percent of the time at the surface, while the well-drained Russell was saturated only 10 percent of the time at a depth of 2 m in the 2 years of the study.

Moore's Woods Toposequence

Soils

Four sites on private land were monitored for water table levels, oxidation-reduction potential, temperature, and matric potential. The sites are located on a Reesville-Ragsdale association of soils on the Wisconsinan till plain in west central Indiana in the N $\frac{1}{2}$ of E $\frac{1}{2}$ of SE $\frac{1}{4}$ of Section 6 of Township 17N, Range 6W and in the S $\frac{1}{2}$ of E $\frac{1}{2}$ of NW $\frac{1}{4}$ of Section 6 of Township 17N, Range 6W in Parke County. The range of elevations for these sites is from 219 to 223 m.

This soil association is extensive on nearly level but undulating swell and swale topography on the Wisconsinan till plain. The poorly drained soil series, Ragsdale and Delmar, developed in concave swales. The Ragsdale soil has a mollic epipedon, and the Delmar soil has an ochric epipedon. The Fincastle lies on the gently sloping convex swells on the till plain. The Russell soil developed on the upper backslope of an interfluvial adjacent to stream channels. This well-drained soil is at a lower elevation than the more poorly drained soils in this sequence (Table 1).

Piezometric head and water table level

The Delmar, Fincastle, and Ragsdale soils generally had a water table at or near the surface some or most of the time during the winter and spring (e.g., graph A of Figure 7 for the Delmar soil). In the Delmar and Fincastle sites,

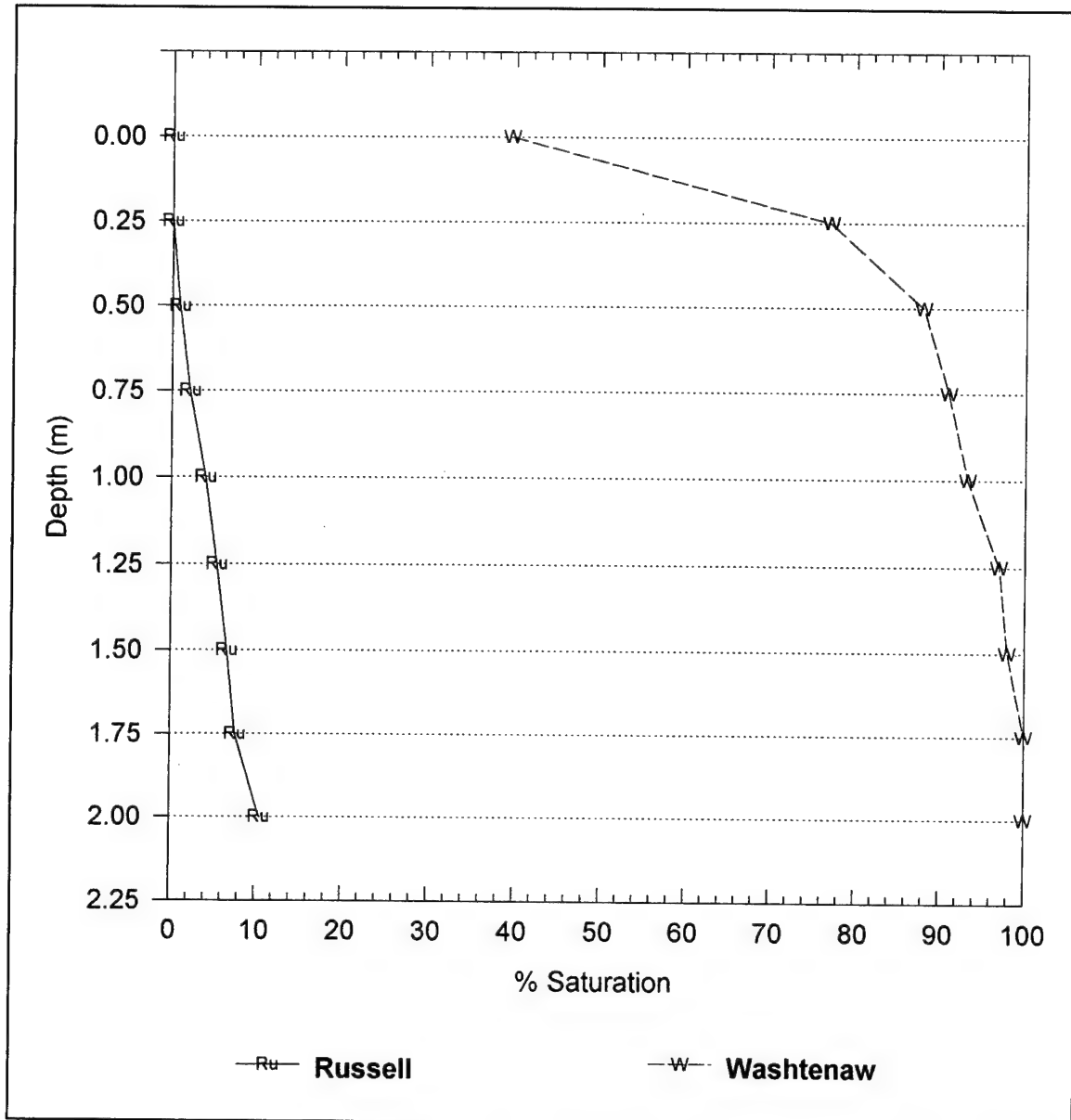


Figure 6. Relative time of saturation in Shades State Park toposequence showing percentage of time each soil horizon was saturated down to a depth of 2 m

the nest of piezometers tended to act as a unit showing little variation in the readings of instruments placed at different depths. The amount of time each soil was saturated, however, was much longer in 1993, with much higher rainfall, than in 1992. In the Russell soil, the water table was deeper, but highly variable in the 2 years.

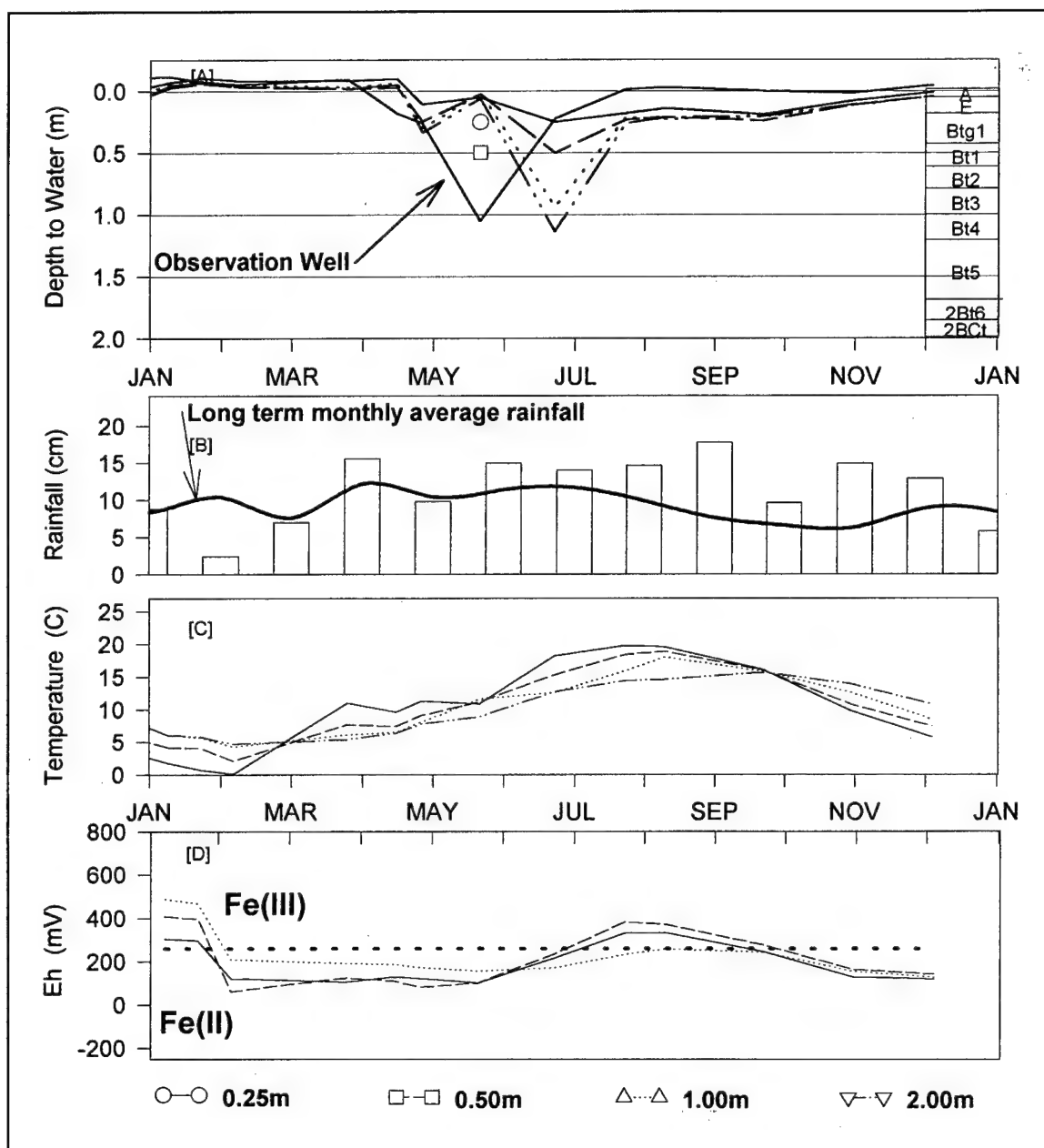


Figure 7. Delmar series data set 1993; [A] depth of water in piezometers and observation well (installed November 1992), [B] rainfall, [C] temperature, [D] redox potential (Eh). Depth of piezometers indicated by symbol and line pattern; unfilled symbols represent empty piezometers

Landscape hydrology

Apparently, there is a strong lateral component of water movement through these soils. The Russell soil in this landscape has a much higher water table than the Russell soil in the Shades State Park toposequence (Figure 8). Precipitation falling on the soils in the nearly level till plain saturates the Fincastle, Delmar, and Ragsdale soils because water is held up by the slowly permeable dense till below the sola. Once saturated, water moves gradually outward, probably through the more permeable B horizons, to the Russell soil on the dissected edges of the till plain. Note, for example, that the rise of the piezometric surfaces and the water table in Russell lags behind the rise in the other soils.

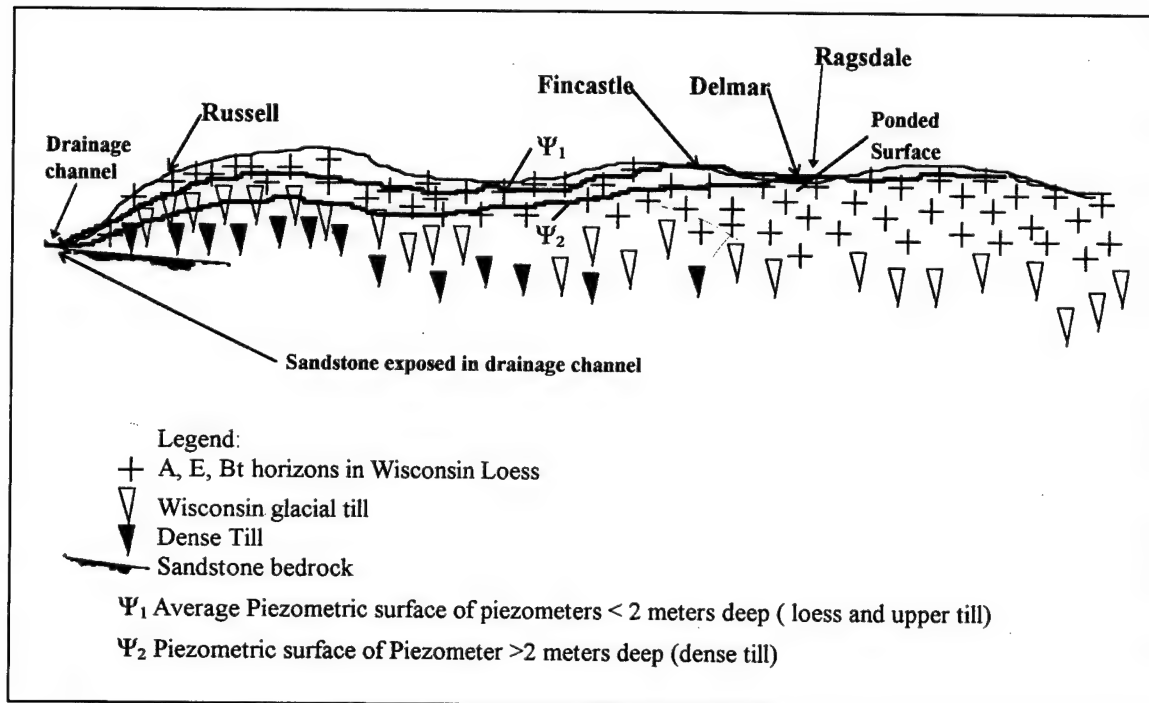


Figure 8. Cross-section sketch through landscape at Moore's Woods showing typical piezometric surfaces in spring

Rainfall

Yearly precipitation totals for 1992 and 1993 (115 and 142 cm, respectively) were above the historical average (104 cm). The water table levels are assumed to be above normal and of longer duration than the average (graph B of Figure 7).

Temperature

The seasonal pattern of temperature rise and fall for the Delmar soil is displayed in graph C of Figure 7. Patterns were similar in the Russell and Fincastle soils. Crossover points for the warm and cool periods occurred in March and September. Temperatures at 25 cm were above 5 °C in 1993 from early March to December.

Redox measurements

Platinum electrodes were installed at the Delmar, Fincastle, and Ragsdale sites. Relative to the thermodynamic Fe(III)-Fe(II) stability line, at 25-cm depth, the Delmar was reduced during the spring and early summer (e.g., graph D of Figure 7). The Fincastle soil was reduced in early spring, and the Ragsdale did not approach reduction. The Ragsdale soil had morphological evidence of significant reduction, however. Apparently, the theoretical equilibrium line does not represent field conditions in this soil, because Fe(II) was identified with the α, α' -dipyridyl test.

Comparison of water table levels among soils

The water table level patterns in the Delmar, Fincastle, and Russell soils generally paralleled each other, but the patterns were different from that of the Ragsdale soil. This reflected the local geography—the three soils were in the same local drainageway, but the Ragsdale soil was in a different one.

Time of saturation

Figure 9 represents the percentage of time that every horizon of the four soils was saturated in 1992 and 1993. Only the Delmar soil showed any significant surface ponding in the 2 years of the study. At lower levels in the profile, however, the water table in the swales stayed within a meter of the surface more than half of the time with the water table in the Fincastle soil being present at a depth of 1 m nearly 50 percent of the time. In the upper 0.25 m, the percentage of time saturated follows fairly regularly the progression Russell < Fincastle < Delmar. The Ragsdale soil is saturated at 0.25 m much less than the Delmar soil, which was unexpected. The elevated water tables reflect the restricting influence of the dense till in the profile.

Soil Morphology and Time of Saturation

Soil scientists have observed for many years that through chemical reduction, soil wetness leaves its mark in the morphology of the soil, especially soil color. Over the years, they have attempted to divide the wet-dry continuum into discrete classes. The continuum has been called a catena, a

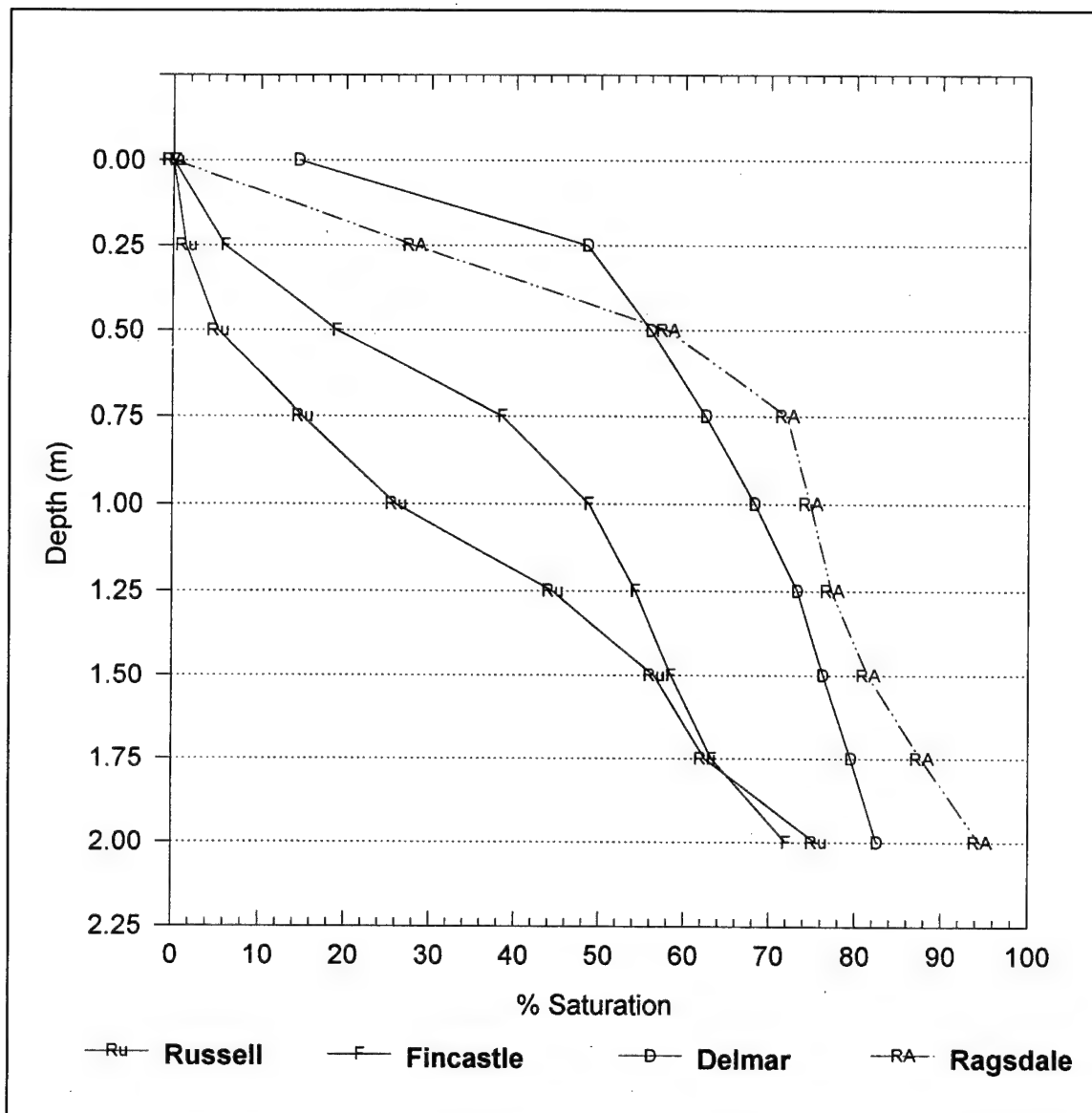


Figure 9. Relative time of saturation in Moore's Woods toposquence showing percentage of time each soil horizon was saturated down to a depth of 2 m

toposequence, or other names. Some of the classifications are soil drainage (typically seven classes), water state classes (eight), and classes defined as part of a more comprehensive classification system, for example Soil Taxonomy, that are defined on a basis of wetness/reduction (variable number of classes). Now the emphasis is to define two classes, hydric and nonhydric soils.

Redoximorphic features are part of the complex morphological description of soil horizons, which includes three aspects of color (hue, value, and chroma) that occur in a variety of positions (matrix, mottles, depletions, concentrations, ped coatings, internal features, etc.) and in different amounts (few, common, many, patchy, continuous, etc.). These horizons are of

various thicknesses and depths in different soils. The question is, How does one integrate all this information to deduce an overall picture of the relative reduction status of the whole soil? A system to derive a single index number was proposed by Evans and Franzmeier (1988) and is described below. It is based on the abundance and the Munsell notation for the dominant color of the matrix, the abundance and color of the mottles, and the abundance and color of clay skins. From these features, color indexes (Evans and Franzmeier 1988) were calculated. The C1 index is based on soil color chroma, specifically,

$$CI_h = \frac{A_m \times CI_m + (A_1 \times CI_1 + A_2 \times CI_2 + \dots A_n \times CI_n) + A_t \times CI_t}{1 + A_t}$$

where

CI_h = CI index for a specific horizon

A_m = abundance of dominant color of matrix with chroma
 CI_m
 $= 1 - (A_1 + A_2 + \dots A_n)$

$A_1, A_2, \dots A_n$ = abundance of mottles with chroma $CI_1, CI_2, \dots CI_n$

A_t = abundance of argillans with chroma CI_t

The C2 index was calculated similarly, but it considered both hue and chroma (Evans and Franzmeier 1988).

To use the index values, one must first choose a certain depth zone. In this zone, the four conditions for saturation should be optimized. Duration of saturation increases with depth, but the organic C content decreases with depth, making it difficult to optimize the period of saturation and the organic matter content. Furthermore, high organic matter content masks the color of other constituents in surface horizons, and many soils are highly leached and have little Fe left in upper horizons that can potentially reflect reduction. These factors must be considered in choosing the depth zone.

Over the years, soil scientists have used the color of the soil below the A horizon but above 1-m depth, especially the color of the upper B horizon, to place soils in wetness/reduction classes. For example, many definitions that represent soil moisture regimes in soil taxonomy refer to colors in the upper part of the argillic horizon, immediately below the A horizon or mollic epipedon, or other similar depths. For this reason, two ranges, 25- to 50-cm depth, and the zone between the bottom of the A horizon down to 100 cm were tried. In wet soils, these depths are saturated much of the time (compared with the surface) and have some organic matter present.

Index values for individual horizons from the Muscatatuck toposequence are shown in Table 2. Weighted averages of the indexes over the two depth zones were calculated and were correlated with the percentage of time the soil was saturated at 25 cm and at 50 cm. This was done for all Alfisols in the study, and correlation coefficients are listed in Table 3. The Ragsdale soil, a Mollisol, was not included because its organic C distribution was so much different from the Alfisols. Correlation coefficients (r) were high, mostly >0.8 . Only a few were significant for individual transects because of the high r values necessary for significance in small populations, but all were significant at the 1-percent level for all sites considered together. The correlations indicate that about 60 to 80 percent (r^2) of the variance in the color index can be explained by the percentage of time a certain depth zone in the soil is saturated. The indexes were also significantly correlated with time of saturation for other soils in Indiana (Evans and Franzmeier 1988) and for some soils in South Carolina (Megonigal, Patrick, and Faulkner 1993).

This approach has the potential for defining hydric soils on the basis of an index value calculated from morphological features. If such a value is used, one must decide where on the continuous scale the line separating hydric soils from nonhydric soils should be drawn.

Conclusions

Traditionally, soil scientists think about soil processes in terms of downward movement of soil solutions. One deduces, however, that lateral movement is very significant in these Indiana soils. Piezometric data show that below the Illinoian and Wisconsinan till plains, soil water is perched on a layer or layers of very slowly permeable material. In the Illinoian area, the limiting layers are the fragipan and the underlying paleosol, while in the Wisconsinan areas, it is dense glacial till. Water moves downward in the profile until it meets one of these layers. Then it moves laterally from the interior of the till plain to the dissected edge where it moves downward to the regional water table.

Soil scientists judge the reduction status of a soil from its morphological features, especially the color pattern. Some quantitative index values were calculated that were significantly correlated with time of saturation in other study areas. These indexes integrate the color features of several parts of a soil horizon to give a number for that horizon and then combine the numbers for several horizons to give a number for a soil pedon or site. One index says, essentially, that the longer a soil is saturated, the grayer the soil (specifically the matrix and ped coatings). The other index says that the wetter the soil, the grayer and the yellower the soil color. When more data are available, these indexes will be related to the percentage of time certain depths in the soil are saturated. If the relationship is strong, it might be possible to define hydric soils using an index number. This number would, most likely,

Table 2
Morphology of Soils in the Muscatatuck Toposequence

Lower Depth, cm	Horizon	Abundance ¹ and Color			Index	
		Dominant	Mottles	Clay Skins	C1	C2
Clermont Soil						
18	Eg	10YR 5/2	m10YR 5/4		2.70	12.70
28	EB1g	10YR 6/2	m10YR 5/6		3.40	13.40
56	EB2g	10YR 6/2	m10YR 5/6		3.40	13.40
84	BE	10YR 6/2	m10YR 5/6		3.40	13.40
107	Bt1\Eg	10YR 6/2	m10YR 5/6	c10YR 6/2	3.50	13.16
	Bt1\Eg	10YR 5/6	m10YR 5/8			
Avonburg Soil						
23	E	10YR 6/3	m10YR 6/1		2.30	12.25
45	BE	10YR 5/4	m10YR 5/2		3.30	13.30
74	Bt1	10YR 5/4	m10YR 5/2	d10YR 5/1	2.53	12.53
107	Bt2	10YR 5/4	m10YR 5/2	d10YR 5/1	2.53	12.53
Rossmoyne Soil						
32	E	10YR 5/4			4.00	14.00
57	BE	10YR 5/4	m10YR 5/6		4.70	14.70
94	Bt1	10YR 4/4	m10YR 5/6	d10YR 5/3	3.85	13.99
	Bt1		m7.5YR 4/4			
120	Bt2	10YR 4/4	m7.5YR 5/6	d10YR 5/4	4.10	14.53
	Bt2			d10YR 6/3		
Cincinnati Soil						
20	E	10YR 6/4			4.00	14.00
38	BE	10YR 6/6			6.00	16.00
51	Bt1	10YR 5/4		d10YR 5/4	4.00	14.00
96	Bt2	10YR 5/6	f10YR 5/2	c10YR 5/4	4.48	17.81
	Bt2		f7.5YR 5/6	c10YR 5/2		
140	2Bt1	10YR 3/4	co10YR 6/2	d10YR 5/4	4.00	10.58
	2Bt1		co7.5YR 5/6			
¹ Explanation of abundance of mottles and clay skins: F = Few, co = Common, m = Many, p = Patchy, d = Discontinuous, c = Continuous.						

Table 3
Correlation Coefficients for Percentage of Time Saturated at Two
Depth Ranges and C1 and C2 Indexes

Index	Depth Range, cm	Depth of Saturation, cm	All	Shades and Moores	Muscatatuck
C1	25-50	25	-0.80 ^a	-0.82	-0.89
C2	25-50	25	-0.87 ^a	-0.87	-0.89
C1	25-50	50	-0.80 ^a	-0.86	-0.69
C2	25-50	50	-0.83 ^a	-0.86	-0.69
C1	Below A horizon to 100	25	-0.91 ^a	-0.95 ^b	-0.82
C2	Below A horizon to 100	25	-0.82 ^a	-0.84	-0.95 ^b
C1	Below A horizon to 100	50	-0.89 ^a	-0.97 ^a	-0.62
C2	Below A horizon to 100	50	-0.84 ^a	-0.86	-0.85

^a Significant at P < 0.01.
^b Significant at P < 0.05.

need to be calibrated locally. Also, it would not apply to some soils, such as very sandy ones, in which the relation of soil color to wetness is poor.

References

- Evans, C. V., and Franzmeier, D. P. (1988). "Color index values to represent wetness and aeration in some Indiana soils," *Geoderma* 41, 353-368.
- Hudnall, W. H., and Wilding, L. P. (1992). "Monitoring soil wetness conditions in Louisiana and Texas." *Proceedings of the Eighth International Soil Correlation Meeting (VIII ISCOM): Characterization, classification, and utilization of wet soils, Louisiana and Texas*. J. M. Kimble, ed., USDA Soil Conservation Service, National Soil Survey Center, Lincoln, NE, 135-147.
- McBride, M. B. (1994). *Environmental chemistry of soils*. Oxford University Press, New York.
- Megonigal, J. P., Patrick, W. H., Jr., and Faulkner, S. P. (1993). "Wetland identification in seasonally flooded forest soils: Soil morphology and redox dynamics," *Soil Sci. Soc. Am. J.* 57, 140-149.

5 Soil Hydrology and Morphology of Three Mollisol Hydrosequences in Minnesota¹

Description of the Study Areas

Locations of five wet soil monitoring sites in Minnesota are shown in Figure 1. The results of work are reported at Thief River Falls, Faribault, and Dalton only, because sites at Cedar Creek and Waseca were installed too recently. A climatic summary for the Thief River Falls, Faribault, and Dalton sites is given in Table 1 and is based on daily observations from 1951 to 1980 at weather stations within approximately 16 km of each monitoring site.

Thief River Falls

Geomorphic setting. The Thief River Falls site lies near the eastern edge of the area inundated by Glacial Lake Agassiz during the late-Wisconsinan glaciation. Soils formed in lake-modified till covered by a thin mantle of reworked lake sediments. The till was derived from the Des Moines Lobe ice advance during the late Wisconsin and has a fine-loamy texture and high calcium carbonate content (Hobbs and Goebel 1982). The wave-planed till has minimal topographic relief; however, a few centimeters in elevation difference can result in significant changes in hydrology and soil characteristics. The landscape is characterized by a mosaic of closed, depressional basins surrounded by uplands rising only a few decimeters in elevation.

Hydrodynamics. The hydrology of this wetland is quite complex; the wetland appears to have recharge characteristics for a few weeks in the early spring following snowmelt possibly via the process of depression-focused recharge as described by Richardson, Wilding, and Daniels (1992) for the

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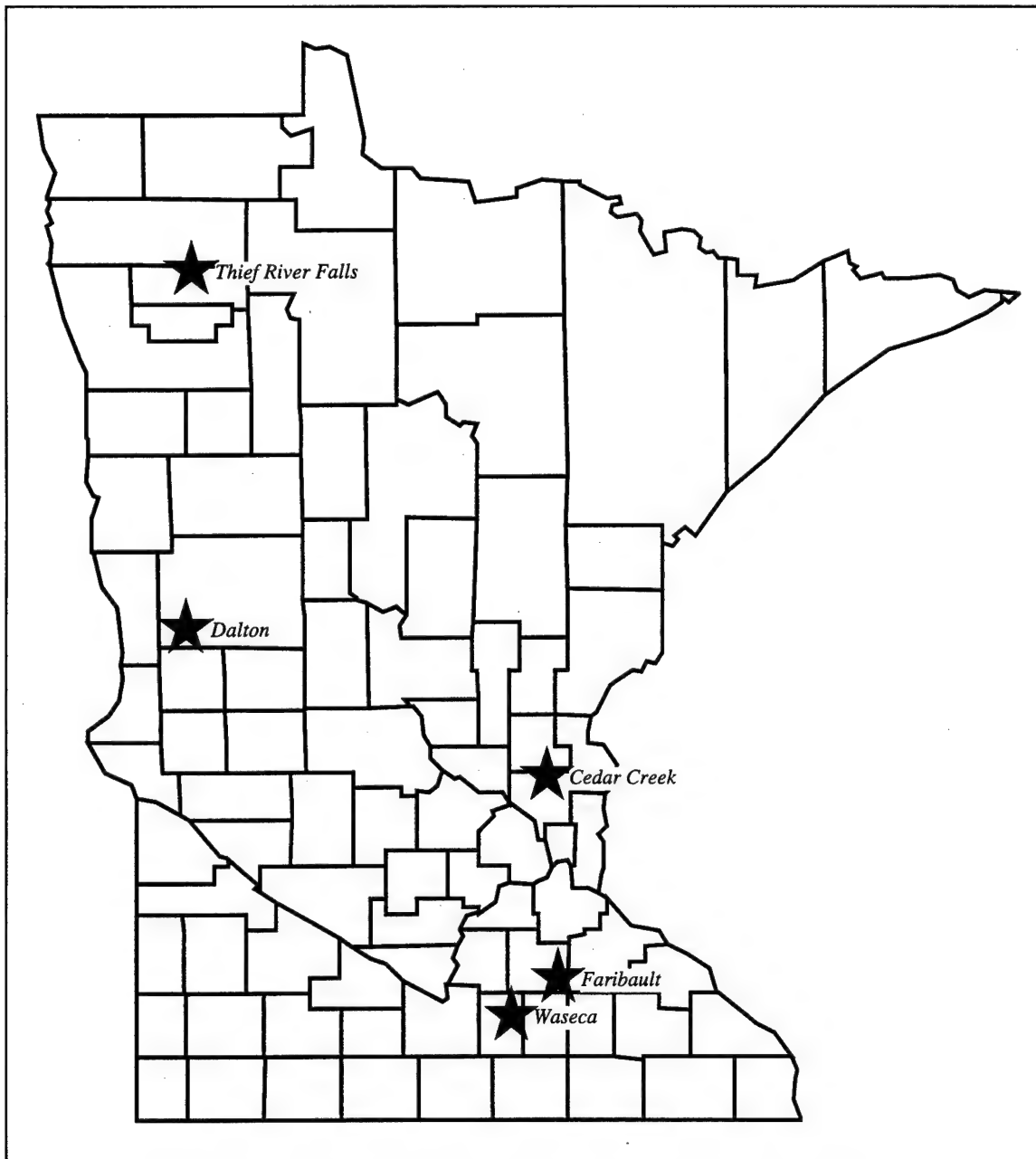


Figure 1. Locations of the five wet soil monitoring study sites in Minnesota

Table 1 Thirty-Year Climate Summary for Thief River Falls, Dalton, and Faribault					
Site	Mean January Temperature, °C	Mean July Temperature, °C	No. Days Minimum Temperature, <0 °C	Mean Annual Precipitation, mm	Mean Annual Snowfall, mm
Thief River Falls	-16.7	20.6	103	536	1,102
Dalton	-14.5	21.7	96	597	1,097
Faribault	-11.4	22.4	75	787	1,092

prairie pothole region. High runoff during spring thaw concentrates surface and near-surface water in topographic depressions and recharges the groundwater. Piezometric data indicate downward water flow for a 1- to 2-week period during March of 1993 where the piezometric pressures above 100 cm were substantially greater than those at 200 cm. This pattern, however, quickly reverses for the next several months where the greatest piezometric pressures were observed at 200 cm and decreased with depth, indicating slight upward water flow or discharge conditions.

Soil characteristics. Four soil profiles were described along a transect from the uplands (Reiner) to a closed depression (Hamre) (Figure 2). The soils grade from Aquic Haploborolls in uplands to Mollic Endoaquepts on the margin of the depression, and Histic Humaquepts in the depressions.

Faribault

Geomorphic setting. The upland soil parent materials at Faribault consist of pre-Wisconsinan glacial till mantled by Wisconsinan-age loess (Kenyon and Renova). Soils on the upper footslope position (Nerstrand) have formed in alluvial/colluvial sediments derived from the immediate hillslope, and the toeslope and drainageway soils (Nerstrand Poorly and Epsom) formed in local alluvial sediments. Because this landscape was not covered by significant glacial drift during the Wisconsin glaciation, an open-surface drainage network exists compared with the deranged surface drainage patterns that characterize most recently glaciated landscapes. The drainageway that passes through the study site flows westward into the North Fork of the Zumbro River and eventually eastward into the Mississippi River. The hillslope has approximately 15 m of topographic relief with discernable summit, shoulder, sideslope, footslope, and toeslope positions. Maximum slope gradients approach 10 percent, and the aspect direction is south to southwest. Slope shape is generally straight along the contour, and convex, straight, and concave shapes exist along the direction of maximum slope. The hillslope is slightly dissected by low relief (< 1 m) drainageways in the direction of maximum slope gradient.

Hydrodynamics. The watershed for the Kenyon, Renova, Nerstrand, and Nerstrand Poorly sites is the local hillslope, whereas the watershed for the Epsom site also includes surrounding hillslopes due to its location in a drainageway. Speculation is that the dense, pre-Wisconsinan till that underlies the loess and alluvial/colluvial sediments restricts vertical water movement, causing some degree of lateral interflow within the soils on the hillslope. The hydrology of the wetland in the drainageway is most likely a groundwater discharge of accumulated flow within the local watershed. There is evidence (rills, matted vegetation, and direct observation) of periodic surface flow in the drainageway.

Soil characteristics. Five soil profiles were described along the hillslope transect (Figure 2). Upland soils (Kenyon, Renova, and Nerstrand positions)

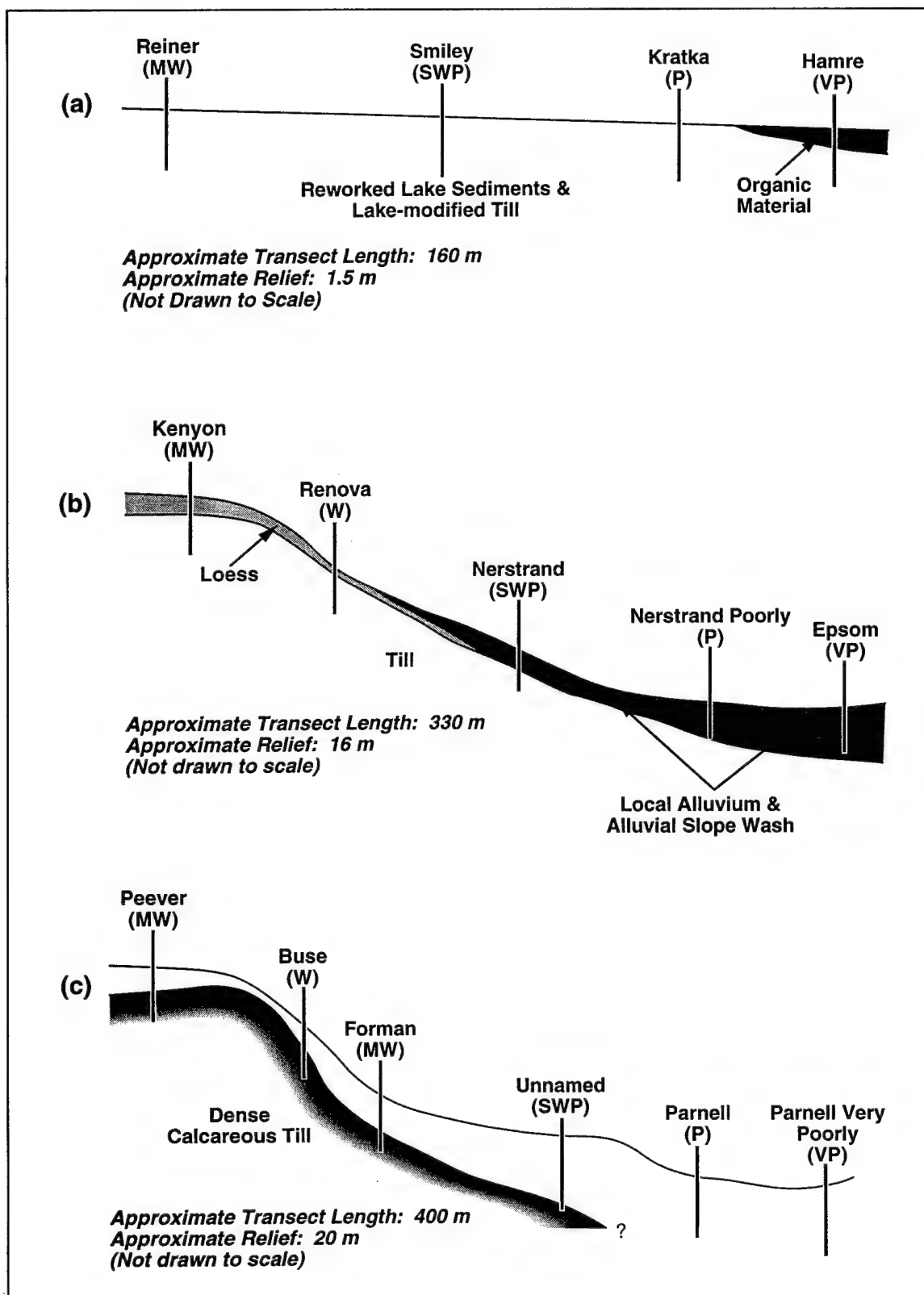


Figure 2. Hillslope transects of the (a) Thief River Falls, (b) Faribault, and (c) Dalton study sites, indicating soil catenary relationships

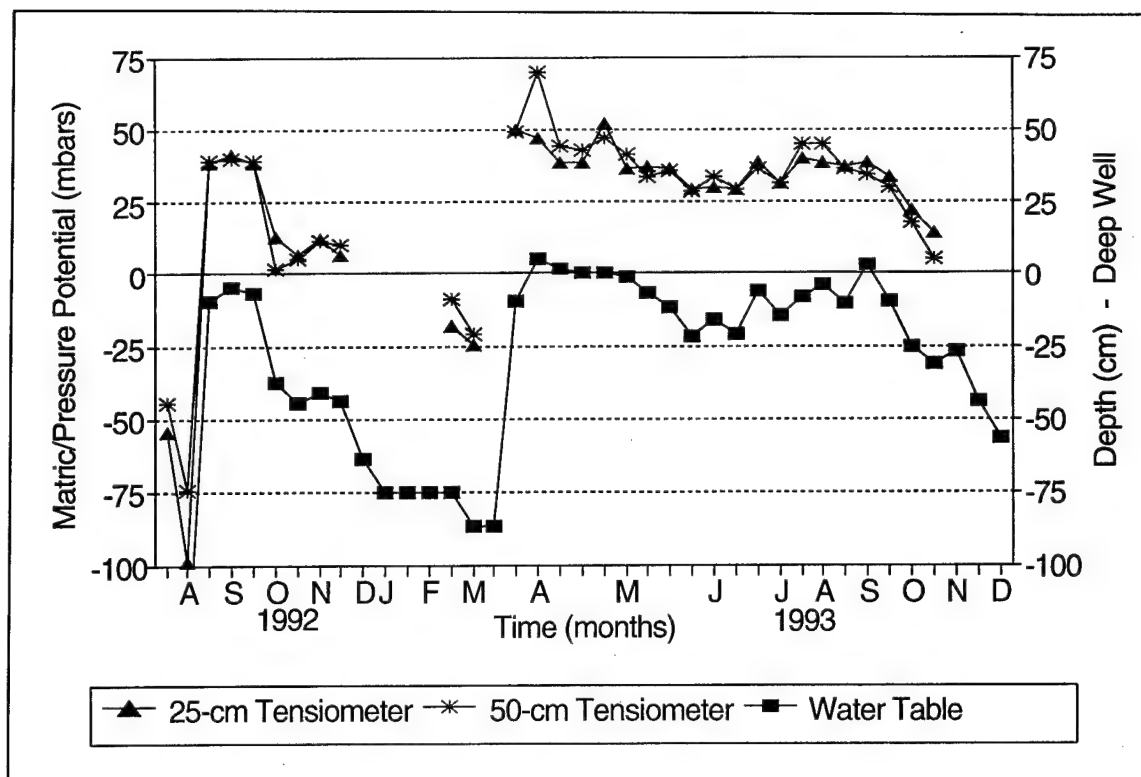


Figure 3. Temporal variations in the water table and soil matric/pressure potential at 25- and 50-cm depths for the Hamre station at Thief River Falls during 1992 and 1993

are Typic Hapludolls and Argiudolls. The toeslope position (Nerstrand Poorly) soils are Cumulic Endoaquolls, and the drainageway position (Epsom) soils are Vertic Endoaquolls.

Dalton

Geomorphic setting. The Dalton site is located on the Alexandria Moraine Complex in western Minnesota. This moraine was produced at the terminus of the Wadena Lobe ice advance during the Wisconsin glacialiation. The Wadena Lobe till was subsequently overridden from the west by the Des Moines Lobe ice advance during the late Wisconsin. The Alexandria Moraine Complex has relatively high local relief (15 to 30 m), a high concentration of lakes, and is interrupted by extensive areas of outwash. Ice-contact features are common in this drift, which is the thickest Wisconsin-age glacial drift in Minnesota (Wright 1972). The hillslope has approximately 18 m of relief and is interrupted by a small bench feature on the lower sideslope (Figure 2). Maximum slope gradients approach 20 percent, and the hillslope contains convex, straight, and concave slope shapes. The hillslope is smooth along the contours such that it is not dissected by secondary drainageways.

Hydrodynamics. The hydrology of this hillslope appears to be quite complex, and it is suspected that the sources of water for the wetland area may vary seasonally. Depression-focused recharge may be a contributing factor during the early spring thaw when the upland soils are still partially frozen. Dense till at a depth of approximately 50 cm in the soils on upper portions of the hillslope suggests that lateral interflow may contribute to the transmission of water from the hillslope to the depressional areas. The presence of a lake on the southern boundary of the site suggests that the lake and the depression may be hydrologically connected and that lake levels may influence soil water table depths during periods when recharge phenomena are not significant. Hence the wetland may receive water from recharge in the early spring, with soil water levels being controlled by discharge phenomena associated with lake levels during other times of the year.

Soil characteristics. Six soil profiles were described along a transect including summit (Peever), shoulder (Buse), lower sideslope (Forman), bench (unnamed), toeslope (Parnell), and depressional (Parnell Very Poorly) hillslope positions (Figure 2). Upland position (Peever, Buse, and Forman) soils are Udic Argiborolls, Udorthentic Haploborolls, and Udic Argiborolls. The soil on the bench position is a Pachic Haploboroll; the toeslope (Parnell) and depressional position (Parnell Very Poorly) soils are Typic Argiaquolls. Results of laboratory analysis were not available at the writing of this report; consequently, soil classifications could change somewhat based on the results of soil analysis. In particular, the presence of argillic horizons was disputed for these soils. Particle-size distribution data and thin-section analysis are being conducted to help resolve this issue.

Methods

Monitoring locations and procedures

Four to six monitoring stations were established at each site (Figure 2). Sampling stations were located along a toposequence traversing the well to very poorly drained hillslope positions. Additional deep monitoring wells were installed between some monitoring stations and along other drainage pathways for comprehensive coverage of hillslope hydrology. Instruments installed at each site are listed in Table 2. In addition, a recording rain gauge and thermometer were installed at one monitoring station on each hillslope. Each site was within 16 km of an extensively instrumented weather station. Relative instrument locations and elevations were surveyed to the nearest centimeter using a geodimeter, and geographic coordinates were recorded within 2 to 3 m using a global positioning system. All instruments were monitored weekly during the first few months of the growing season and biweekly otherwise. In addition, pH of water in the piezometers, soil reaction to α, α' -dipyridyl dye at four depths per station, sky conditions, and time were recorded.

Table 2 Instrumentation Installed at the Minnesota Wet Soil Monitoring Sites					
Site	Wells	Piezometers	Tensiometers	Thermocouples	Pt Electrodes
Thief River Falls ¹					
Hamre	300 cm	25, 50, 100, 200 cm	25, 50, 75, 100 cm	10, 25, 50, 100 cm	25, 50, 100 cm
Kratka	300	25, 50, 100, 200	25, 50, 75, 100	10, 25, 50, 100	25, 50, 100
Smiley	300	25, 50, 100, 200	25, 50, 75, 100	10, 25, 50, 100	25, 50, 100
Reiner	300	25, 50, 100, 200	25, 50, 75, 100	10, 25, 50, 100	25, 50, 100
Faribault ¹					
Epsom	300	25, 50, 100, 200	25, 50, 75, 100	10, 25, 50, 100	25, 50, 100
Nerstrand P	300	25, 50, 100, 200	25, 50, 75, 100	10, 25, 50, 100	25, 50, 100
Nerstrand SWP	300	25, 50, 100, 200	25, 50, 75, 100	10, 25, 50, 100	25, 50, 100
Renova	300	25, 50, 100, 200	25, 50, 75, 100	10, 25, 50, 100	25, 50, 100
Kenyon	300	25, 50, 100, 200	25, 50, 75, 100	10, 25, 50, 100	25, 50, 100
Upgradient in Drainageway (WA)	300	--	--	--	--
Dalton ²					
Parnell VP	300	25, 50, 100, 200	25, 50, 75, 100	10, 25, 50, 100	25, 50, 100
Parnell P	300	25, 50, 100, 200	25, 50, 75, 100	10, 25, 50, 100	25, 50, 100
Bench	--	25, 50, 100, 200	25, 50, 75, 100	10, 25, 50, 100	25
Forman	300	25, 50, 100, 200	25, 50, 100	10, 25, 50, 100	--
Buse	300	25, 50, 100, 200	25, 50, 100	10, 25, 50, 100	--
Summit (WC)	300	--	--	--	--
Upper Bench (WB)	300	--	--	--	--
Lower Bench (WA)	300	--	--	--	--
Upgradient in Drainageway (WD)	300	--	--	--	--
¹ Installed fall 1991. ² Installed fall 1992.					

Precipitation record

Thief River Falls. Monthly rainfall amounts fluctuated considerably during the 1992 growing season with below normal rainfall for all months except July and September. A monthly high rainfall of 178 mm was recorded during September. Cumulative May through October rainfall for 1992 was near the 30-year average. Monthly rainfall was above normal from June through September for 1993. Spring and summer rainfall was considerably above normal in the upper midwest during 1993, causing extensive flooding and ponding throughout the region. May through September cumulative rainfall was approximately 100 mm above normal.

Faribault. Monthly rainfall quantities were below normal at Faribault throughout the growing season during 1992 with the exception of October, when 120 mm of rainfall was recorded. Cumulative May through October rainfall was approximately 100 mm below normal. During 1993, higher rainfall patterns throughout the region were also reflected at Faribault where May through October rainfall was 64 mm above the 30-year normal. A monthly peak of 175 mm was recorded in July.

Dalton. Biweekly rainfall and other monitoring data were only recorded for 1993 for the Dalton site because the site was installed during the fall of 1992. Annual patterns of rainfall indicate above normal rainfall during the first portion of the growing season (May through July) and below normal rainfall from August through October. Cumulative May through October rainfall was approximately 64 mm above normal.

Results and Discussion

Thief River Falls

Soil saturation and reduction. Deep well (Figure 3) and piezometer data from 200 cm (Figure 4) show the same general trends for 1992 and 1993. Note that the deep wells were not installed until July of 1992, whereas piezometers were installed during the fall of 1991. These observations indicate a rapid rise in surficial water tables during March for all landscape positions followed by a decline until September when a slight rise was observed both years. Surficial water table levels declined throughout the winter months (November through March) as near-surface soil temperatures fell below 0 °C, and a majority of the surface water was sequestered as snow and/or ice until the spring thaw. The March through August decline in surficial water table levels was much more pronounced during 1992 when quantities of rainfall were less. The surficial water table (or assumed water table from the 200-cm piezometers) was only observed within 25 cm of the surface for longer than 2 weeks at the Kratka and Hamre sites (Table 3). By early May of 1992, the surficial water table was within 25 cm of the surface at the Hamre site and remained above that level for the next 10 weeks. The water table rose within

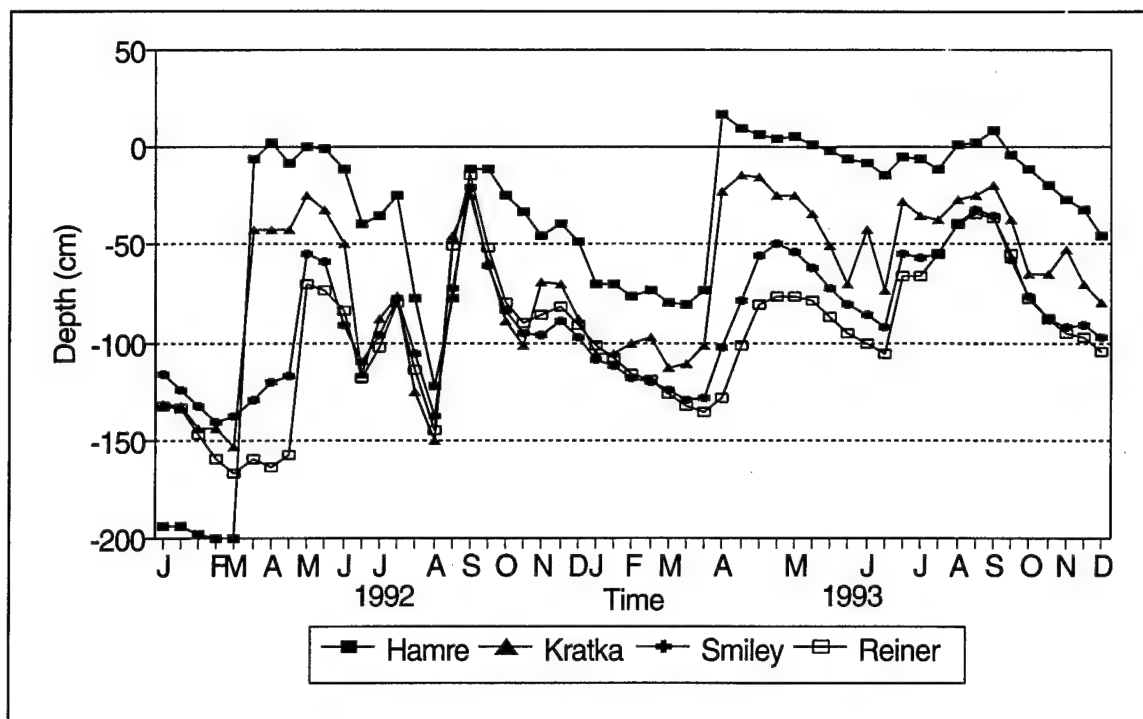


Figure 4. Temporal variations in the piezometric surface at 200 cm for all soils at Thief River Falls during 1992 and 1993

25 cm of the surface again in late September for another 5 weeks. The water table at the Kratka site was within 25 cm of the surface for approximately 2 weeks in early May and less than 2 weeks in late September. The water table at the Smiley and Reiner sites was not within 25 cm of the surface with the exception of a single observation in late September. Rainfall was substantially greater during the summer of 1993, and similar surficial water table responses were observed for the four sites except that the duration of time that the water table was within 25 cm of the surface increased from 2 to 6 weeks for the Kratka and from 15 to 26 weeks for the Hamre soils (Table 3).

Tensiometer data from the 25-cm depth for the Hamre site indicate that the soil was saturated above the water table (Figure 3). Thus periods of soil saturation at the 25-cm depth are a couple of weeks longer than the time period when the water table is above this depth. Note that when the water table is approximately 40 cm below the soil surface, the tensiometer recorded a positive pressure at 25 cm indicating saturated or near-saturated soil conditions at least 15 cm above the observed water table depth. Similar trends were observed for the Kratka soil. The actual height of capillary rise is somewhat difficult to evaluate due to the dynamic nature of the soil hydrology and stratigraphic influences. The close correlation between seasonal patterns of change in water table elevations and soil water potential suggests that capillary rise may explain the presence of positive soil water potentials above the observed water table.

Table 3
Summary of 1992 and 1993^a Hydric Soil Indicator Information at the Thief River Falls Study Site

Station	Soil Family	Weeks Piezometric Surface Within 25 cm ^b		Weeks Water Table Within 25 cm ^c , 1993		Weeks Redox Potential Below 300 mV at 25 (and 50) cm ^d		Hydric Soil Indicators ^e	A-hor. Matrix Color (depth) B-hor. Matrix Color (depth)
		1992	1993	1992	1993	1992	1993		
Reiner	Fine-loamy, mixed, Aquic Haploboroll	< 2 ^f	0	< 2 ^f		0(0)	0(2)	None	10YR 2/1 (0-19 cm) 10YR 3/2 (19-32 cm)
Smiley	Fine-loamy, mixed, frigid, Aquic Haploboroll	< 2 ^f	0	< 2 ^f		0(0)	0(0)	None	10YR 2/1 (0-28 cm) 10YR 4/2 (28-40 cm)
Kratka	Sandy over loamy, mixed, frigid, Mollic Endoaquept	2 ^g	7 ^g	6 ^g		2(0)	15 ^g (10 ^g)	FM3	10YR 2/1 (0-20 cm) 10YR 5/2 (20-42 cm)
Hamre	Fine-loamy, mixed nonacid, frigid, Histic Humaquept	15 ^g	28	26		< 2 ^f (< 2 ^h)	21(21)	FM2	2.5Y 5/2 (0-15 cm) ^h 2.5Y 5/2 (15-31 cm)

^a Based on observations recorded between 15 April-15 November 1992 and 15 May-15 October 1993.

^b Based on depth to piezometric surface readings from 200-cm piezometers read at 2-week intervals; number of weeks based on time period inclusive between consecutive readings all of which were above 25 cm.

^c Based on depth to water table readings from 300-cm wells read at 2-week intervals; number of weeks based on time period inclusive between consecutive readings all of which were above 25 cm.

^d Based on electrode potential readings (corrected to pH 7) from 25- (and 50-) cm platinum electrodes read at 2-week intervals; number of weeks based on time period inclusive between consecutive readings all of which were below 300 mV.

^e Categories from DRAFT of Testing Version (February 1, 1994) of Field Indicators of Saturated Hydric Soils in the United States.

^f Only one observation below piezometric surface, below water table, or with electrode potential below 300mV during observation period.

^g Occurred during two or more separate periods.

^h Oxidized rhizospheres (5YR 3/4) present.

Seasonal patterns of redox potential, in general, corresponded with the duration of soil saturation. Soil redox potentials from April through October at the 25-cm depth indicate lower potentials for the Hamre and Kratka sites (Figure 5). These differences were more pronounced during the wetter summer of 1993. In 1992, redox potentials dropped from approximately 500 mV to 300 mV for the Kratka and Hamre sites when the surface soil was near saturation, although this trend was not consistent. Redox potentials in the Hamre soil increased during the drier period during August of 1992 then dropped to near 300 mV again in September as water table elevation peaked before the winter decline. Unfortunately, soil redox potentials were not measured in the early spring, so the temperature and soil moisture conditions leading to low redox potentials following snowmelt could not be evaluated. Redox potentials were already below 300 mV by mid-May when the first records were made in 1993 and remained below 200 mV from June through September for both the Hamre and Kratka sites. The redox potentials for unsaturated soils at Thief River Falls generally remained above 500 mV.

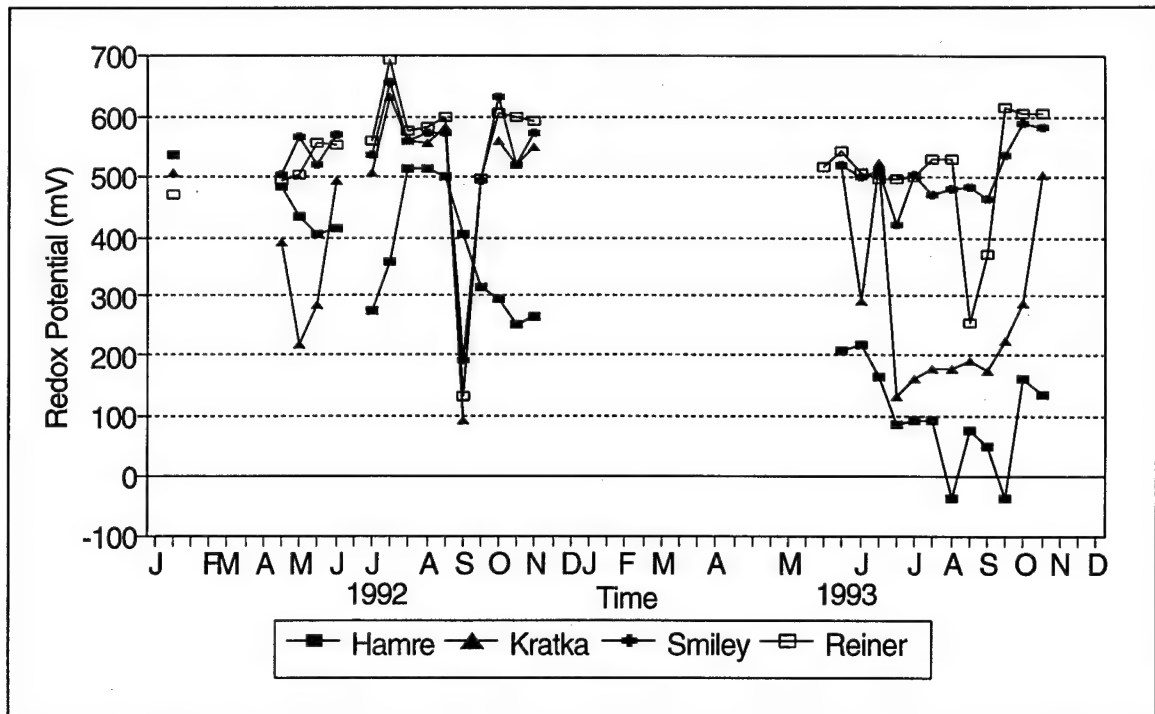


Figure 5. Temporal variations in soil redox potential at 25 cm for all soils at Thief River Falls during 1992 and 1993

Effects of soil temperature. Measurements of soil temperature at 25 cm below the soil surface indicate that soil temperatures are above 5 °C (41 °F) from the first week of May through the middle of October (Figure 6). The inferred growing season for the frigid soil temperature regime (U.S. Department of Agriculture (USDA) Soil Conservation Service 1991) begins on the same date, but would end at least 2 weeks earlier than estimates based on measured soil temperatures at the 25-cm depth (Table 4). Growing season

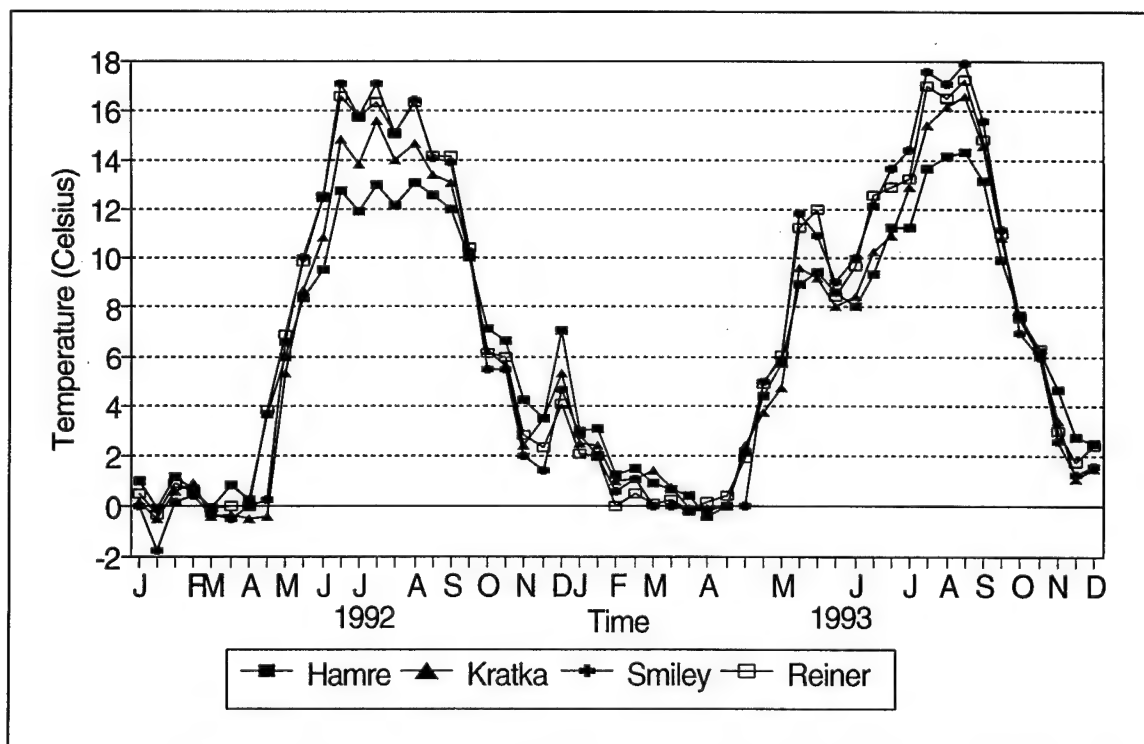


Figure 6. Temporal variations in soil temperature at 25 cm for all soils at Thief River Falls during 1992 and 1993

Table 4 Estimates of the Growing Season at Thief River Falls Based on Soil Temperature Measurements, the Soil Temperature Regime, and Air Temperature Data		
Method	Beginning Date	Ending Date
Soil Temperature > 5 °C at 25-cm depth	1 May	15 October
Inferred from Frigid Regime	1 May	30 September
Inferred from Air Temperature Data (28 °F Threshold)	8 May	1 October
Inferred from Air Temperature Data (32 °F Threshold)	19 May	22 September

estimates based on long-term air temperature data with temperature thresholds of 28 and 32 °F would shorten the growing season from 1 to 3 weeks in the spring and 2 to 3 weeks in the fall.

If one only considers soil saturation during the time period when soil temperature at 25 cm is above 5 °C, the Kratka site was not saturated above

25 cm in 1992 and was saturated above 25 cm for 8 weeks in 1993. The Hamre soil was saturated above 25 cm for 8 weeks in 1992 and for 19 weeks in 1993 when the soil temperature was above 5 °C. Temperature thresholds for the onset of reduction could not be determined for this site due to lack of soil redox data in the early spring.

Soil morphological indicators. The depth of the seasonally high surficial water tables for the Hamre (above surface), Kratka (18-25 cm), Smiley (25-30 cm), and Reiner soils (25-30 cm), and the presence of low redox potentials suggest a moisture regime favorable for the genesis of soil redoximorphic features. Soil morphological features associated with increasing duration of saturation include accumulation of organic material on the mineral soil surface, apparent oxidized rhizospheres, low chroma (less than or equal to 2) matrix below the A horizon, and high chroma redoximorphic concentrations. The soil at the Hamre site has a 38-cm-thick organic surface layer underlain by a grayish brown (2.5Y 5/2) A horizon over a 2.5Y 5/2 Bkg horizon extending to the lower extent of the described soil profile at 155 cm. The thickness of the histic epipedon suggests that small areas of Histosols are likely to occur within this basin. Prominent strong brown (7.5YR 4/6) mottles (apparent redox concentrations) were present in the A horizon and were associated with live root channels. Prominent, strong brown (7.5YR 4/6 and 5/6) mottles (apparent redox concentrations) increased in abundance with depth throughout the B horizons and were associated with a grayish brown (2.5Y 5/2) matrix. According to the February 1994 draft version of the proposed indicators of hydric soils by the Natural Resources Conservation Service, Hamre soil exhibits indicator FM2, which states the following:

presence of muck either on the surface or in the mineral surface layer having a combined thickness of 10 cm or more.

Progressing upslope, the soil at the Kratka site does not have an accumulation of organic material on the soil surface. However, the surface soil has been disturbed by agricultural tillage, such that a thin organic layer, if present, would have been incorporated into the Ap horizon. This soil formed at the margin of the depressional basin and contains stratified sands that may be remnants of a lake-margin beach deposit. Consequently, the substratum contains sandy and gravelly materials beneath the A horizon in contrast to the Hamre, Smiley, and Reiner soils, which have loamy substratums. Redoximorphic concentrations are not evident in the Ap horizon, which is a black (10YR 2/1) loam. The upper B horizon (20-42 cm) has a low chroma matrix (10YR 5/2) with strong brown (7.5YR 4/6) masses (40 percent) and dark grayish brown (10YR 4/2) mottles. These color patterns suggest a combination of both redox concentrations and depletions in a zone of fluctuating soil saturation. The upper nonsandy B horizon is from 56-75 cm and has a grayish brown (10YR 5/2) matrix with prominent, strong brown (7.5YR 4/6) mottles (apparent redox concentrations). This soil could be interpreted as meeting proposed indicator FM3, which states the following:

directly beneath an ochric or umbric epipedon having a chroma 2 or less and thickness of 30 cm or less, 60 percent or more of the matrix is depleted of iron in all layers to a depth of 35 cm or more and has (b) value 5 or more and chroma 2 or less and has distinct or prominent redox concentrations as iron masses.

This would assume that the 10YR 5/2 zone in the Bw1 horizon would be interpreted as depletions and that the 7.5YR 4/6 mottles were redox concentrations as iron masses.

The two upland sites (Smiley and Reiner) both have black (10YR 2/1) A horizons at least 19 cm thick underlain by Bw horizons with dark to very dark grayish brown (10YR 4/2 to 3/2) colors. The lack of redox concentrations in the uppermost B horizon appears to distinguish these upland soils from the soil at the Kratka site. Prominent strong brown (10YR 4/6) mottles begin to increase in abundance between 30 to 40 cm for both of these soils, corresponding to the maximum height of the observed water table for 1992 and 1993. These two soils did not meet any of the proposed morphological indicators for hydric soils.

Soil morphological changes associated with increased duration of saturation at the Thief River Falls site include (a) increased accumulation of organic materials on the mineral soil surface; (b) redoximorphic concentrations in the A horizon associated with oxidized rhizospheres; and (c) low chroma (≤ 2) matrix for the uppermost B horizon with prominent strong brown (7.5YR 4/4 to 4/6) mottles (apparent redox concentrations).

The glacial sediments that form the parent material for the soils at the Thief River Falls site have a low chroma. Consequently, the color differences associated with differing durations of soil saturation are not prominent, and the identification of hydric soils based solely on soil characteristics can be somewhat tenuous. Although the elevation gradient is quiet subtle, it has a significant effect on the hydrology of the soils within these landscapes. Because landscape position is a critical factor for soil hydrology, which in turn affects soil genesis, landscape position should also be considered, implicitly if not explicitly, when defining hydric soils for these landscapes.

Faribault

Soil saturation and reduction. Seasonal fluctuations in the piezometric surface measured at 200-cm depth and the surficial water tables followed similar patterns for 1992 and 1993. Deep wells were not installed until October of 1992; hence, the water table record is incomplete. However, because substantial differences were not observed between the piezometric surface and water table levels in 1993, the 200-cm piezometers should give a reasonable approximation of the water table response for 1992. Surficial water tables across the entire hillslope had similar patterns of seasonal response for both years. Beginning in January, water table elevations fell until mid-March, then

rose rapidly in response to spring thaw. Water table levels gradually fell throughout the summer, then rose again in mid- to late September and began to decline again in January as the cycle continued. Sustained episodes of rising water tables appear to be associated with the release of moisture associated with spring thaw (March and April) and reductions in evapotranspiration rates during the late fall (September) before the soil freezes. Episodes of falling water tables appear to be associated with increased evapotranspiration in the spring and summer (May through September) and the storage of precipitation as surficial ice and snow (January through March). During periods of rising water tables, the water table elevation peaked first in the lower landscape positions (Epsom) with a 2- to 4-week lag before the water table peaked on the shoulder of the hillslope (Renova). During 1992 (less precipitation), the water table dropped 150 to 200 cm across the landscape between mid-May and September, then rebounded somewhat during October. During the summer of 1993, water table levels dropped less than 1 m due to higher quantities of rainfall. The response of the water table for the soils at the Nerstrand and Kenyon sites was nearly coincident throughout 1992, despite the fact that the Nerstrand site is on a toeslope and the Kenyon site is on the hillslope summit. The water table of the soil at the Renova site was never within 25 cm of the soil surface. The rapid rise and fall of the water table is indicative of its shoulder hillslope position. Depth to the water table followed the following trend across the landscape: Renova > Kenyon > Nerstrand > Nerstrand Poorly > Epsom. The duration of saturation at a 25-cm depth increased for all hillslope positions from 1992 to 1993 (Table 5). There were a few observations in early spring where the piezometric pressure was greater at 25- and/or 50-cm depths than at the 100- or 200-cm depths. The higher piezometric pressures at shallow depths could indicate either water accumulation above an aquatard (dense till) or recharge conditions (downward water flow).

The effect of greater precipitation during the summer of 1993 is apparent by comparing redox potential measurements between these 2 years (Figure 7). Redox potential at a 50-cm depth separates the Epsom and Nerstrand Poorly sites from the rest of the landscape, and there was greater separation between the Nerstrand Poorly and Epsom during 1993. At the three upper hillslope positions, the measured redox potential remained above 400 mV for much of 1992 and 1993 at both 25- and 50-cm depths. The soils at the Nerstrand Poorly and the Epsom sites maintained redox potentials below 300 mV throughout the summer and early fall as the soil remained saturated at the 50-cm depth. The redox potential for the Nerstrand Poorly site remained fairly constant throughout the time period; however, the redox potential at the Epsom site fluctuated. On three occasions, the redox potential fluctuated from approximately 200 to >350 mV over 2 weeks at a 50-cm depth (Figure 7). The redox potential at the 25-cm depth fluctuated from less than 300 to greater than 650 mV during this same time period. The development of periodic oxic conditions may explain these fluctuations. The Epsom site is located in a broad drainageway, and the soils are composed of stratified and highly permeable sands and gravels. Consequently, high water flow rates may occur following high rainfalls that could induce oxic conditions in these soils.

Table 5
Summary of 1992 and 1993^a Hydric Soil Indicator Information at the Faribault Study

Station	Soil Family	Weeks Piezometric Surface Within 25 cm ^b		Weeks Water Table Within 25 cm ^c , 1993		Weeks Redox Potential Below 300 mV at 25 (and 50) cm ^d		Hydric Soil Indicators ^e	A-hor. Matrix Color (depth) B-hor. Matrix Color (depth)
		1992	1993	1992	1993	1992	1993		
Kenyon	Fine-loamy, mixed, mesic, Typic Hapludoll	<2 ^f	6	4		0(<2 ^f)	0(0)	None	10YR 2/1 (0-26 cm) 10YR 3/3 (26-35 cm)
Renova	Fine-loamy, mixed, mesic, Typic Argiudoll	0	4	2		0(0)	0(0)	None	10YR 3/2 (0-24 cm) 10YR 4/4 (24-40 cm)
Nerstrand	Fine-silty, mixed, mesic, Typic Hapludoll	2 ^f	6	6		<2 ^f (0)	0(0)	None	10YR 2/1 (0-77 cm) 10YR 5/3 (77-125 cm)
Nerstrand Poorly	Fine-silty, mixed, mesic, Cumulic Endoaquoll	9 ^g	9 ^g	7 ^g		2(4)	20 ^g (18)	MM5	10YR 2/1 (0-64 cm) 10YR 3/2 (64-88 cm)
Epsom	Fine-silty, mixed, mesic, Vertic Endoaquoll	14 ^g	17 ^g	5 ^g		0(2 ^h)	2 ^g (11 ^h)	None	N 2/0 (0-63 cm) 10 YR 4/1 (63-75 cm)

^a Based on observations recorded between 15 April-15 October 1992 and 1 May-15 October 1993.

^b Based on depth to piezometric surface readings from 200-cm piezometers read at 2-week intervals; number of weeks based on time period inclusive between consecutive readings all of which were above 25 cm.

^c Based on depth to water table readings from 300-cm wells read at 2-week intervals; number of weeks based on time period inclusive between consecutive readings all of which were above 25 cm.

^d Based on electrode potential readings (corrected to pH 7) from 25- (and 50-) cm platinum electrodes read at 2-week intervals; number of weeks based on time period inclusive between consecutive readings all of which were below 300 mV.

^e Categories from DRAFT of Testing Version (February 1, 1994) of Field Indicators of Saturated Hydric Soils in the United States.

^f Only one observation below piezometric surface, below water table, or with electrode potential below 300 mV during observation period.

^g Occurred during two or more separate periods.

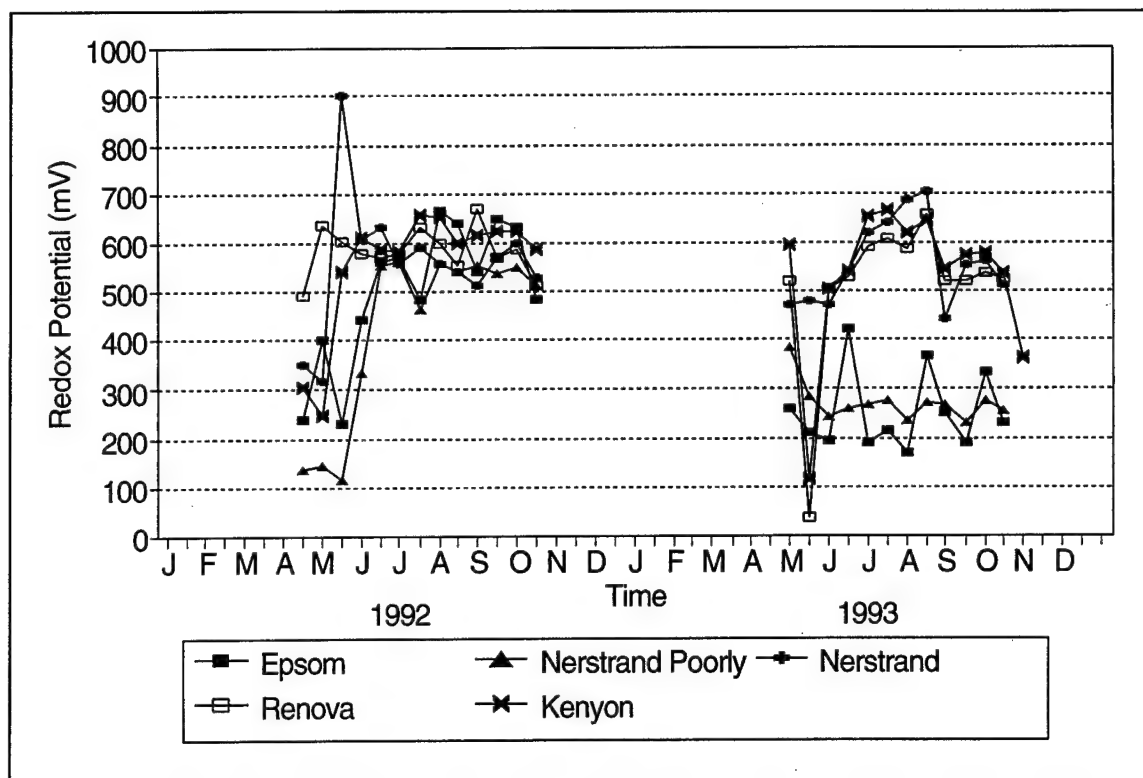


Figure 7. Temporal variations in soil redox potential at 50 cm for all soils at Faribault during 1992 and 1993

The Nerstrand Poorly site is on the fringe of the drainageway and has a much smaller specific catchment area than the central portion of the drainageway; hence, potential flow rates are much lower for the Nerstrand Poorly site.

Positive soil water potentials were observed at the 25-cm depth when the water table was approximately 30 to 40 cm from the surface for the Nerstrand Poorly site. As the water table fell below 40 cm, the soil water potential at the 25-cm depth became negative, in most cases. A similar trend was observed at the 50-cm depth with positive soil water potentials when the water table was 75 to 80 cm below the surface. Similar trends were also observed for the Epsom site.

Effects of soil temperature. Measurements of soil temperature at 25 cm below the soil surface indicate that soil temperatures are above 5 °C from the first week of May through mid-October. The inferred growing season for the mesic soil temperature regime (USDA Natural Resources Conservation Service 1991) begins almost 2 months earlier and would end 2 weeks later, approximately 2.5 months longer than estimates based on soil temperature (Table 6). Growing season estimates based on 50-percent probabilities of encountering a 28 °F air temperature threshold closely agreed with the estimate based on soil temperature. Estimates based on 32 °F air temperatures shortened the growing season estimate by approximately 3 weeks compared

Table 6**Estimates of the Growing Season at Faribault Based on Soil Temperature Measurements, the Soil Temperature Regime, and Air Temperature Data**

Method	Beginning Date	Ending Date
Soil Temperature > 5 °C at 25-cm depth	1 May	1 November
Inferred from Mesic Regime	1 March	31 October
Inferred from Air Temperature Data (28 °F Threshold)	28 April	13 October
Inferred from Air Temperature Data (32 °F Threshold)	7 May	1 October

with the soil temperature estimate. Redox potential measurements taken on 15 April of 1992 indicate low (<100 mV) redox potentials at 25 cm in the Nerstrand Poorly soil when the observed soil temperature was 2.6 °C at 25 cm. At 50 cm, the redox potential was 150 mV and the soil temperature was 2.7 °C. Piezometers at all depths indicated piezometric surfaces above 25 cm (wells not yet installed). Redox potential measurements were not taken before 1 May during 1993. Very little can be determined from a set of observations from a single point in time; however, the observations on 15 April 1992 suggest the possibility that low redox potentials, and the inferred microbial activity, may occur at soil temperatures below 5 °C for this landscape.

If soil saturation is only considered during the time period when soil temperature at 25 cm was above 5 °C, only the soils at the Nerstrand Poorly and Epsom sites were saturated at 25 cm for longer than 2 weeks in 1992. The soils at all hillslope monitoring sites were saturated for 3 weeks or longer at 25 cm during 1993 (Table 5). Extended periods of low redox potentials (<300 mV) are associated with saturation during the growing season with the exception of the Epsom site, which may have periodic oxic conditions.

Soil morphological indicators. The observed seasonal high surficial water tables based on 2 years of monitoring the soils on this transect are as follows: Epsom (above surface), Nerstrand Poorly (5-15 cm), Nerstrand (5-15 cm), Renova (15-30 cm), and Kenyon (5-20 cm). Extended periods of low redox potentials were observed for the two lowest sites on the hillslope (Epsom and Nerstrand Poorly). The following soil morphological trends were observed with increasing duration of saturation and reduction (Renova < Kenyon < Nerstrand < Nerstrand Poorly < Epsom): (a) decreased chroma of the surface soil horizon (2 to 0); (b) increasing thickness of the A horizon (24 to 77 cm); (c) decreasing chroma of the upper B horizon (4 to 1); and (d) prominent, strong brown (7.5YR 4/6) mottles (apparent oxidized rhizospheres in the A horizon with a matrix chroma of 1 or less), from 0 to 20 cm for Nerstrand Poorly or from 25 to 63 cm for Epsom.

The soil at the Nerstrand and subsequent upslope sites do not have redoximorphic concentrations in the A horizons, and the upper B horizons do not have a chroma of 2 or less. The Nerstrand Poorly site meets proposed morphological indicator for hydric soils MM5, which states the following:

presence of distinct or prominent redox concentrations on ped faces or ped interiors in a zone more than 10 cm thick in the upper 30 cm of the mineral soil and has matrix value of 3 or less and chroma 1 or less and redox concentrations as masses with value 4 or more and chroma 4 or more.

The Epsom soil does not meet any of the proposed morphological criteria for hydric soils because redox concentrations within the upper 30 cm do not occupy a zone greater than 10 cm thick.

Dalton

Soil saturation and reduction. Monitoring data from the Dalton site must be interpreted with considerable caution because only 1 year of data is available and rainfall for that year was above normal during the early part of the growing season. Data from subsequent years will be needed to accurately characterize the water regime for the soils in this landscape. First year measurements indicated that the water table was less than 25 cm from the surface for 7 weeks at the Parnell site and 16 weeks at the Parnell Very Poorly site from early April through mid-July. The water table rose rapidly (175 cm over 2 weeks) due to the spring thaw and possible depression-focused groundwater recharge. Piezometers indicate higher piezometric pressures at 25 cm than at 200 cm, which would support recharge hydrology. During the period of high water tables (March through June) the piezometric surfaces were consistently in the following order: 25 cm > 200 cm > 100 cm > 50 cm. The possibility is being considered that the water table elevations are being influenced by the water level in an adjacent lake. Consequently, monitoring lake water elevations will begin during 1995. Water tables at the Parnell and Very Poorly sites dropped beginning in early July and rose again somewhat during the fall. With the exception of three observations below the 150-cm depth at the unnamed site, water was not observed in any of the piezometers at other locations along the hillslope during 1993 (Table 7).

Observed soil water potentials for 1993 did not indicate positive pressures (saturation) above the water table. For example, as the water table fell below the 25- or 50-cm-deep tensiometers, the soil water potential became negative at the Parnell Very Poorly site. Positive soil water potentials at the 25-cm depth were only found at the Parnell Very Poorly site in 1993. These positive potentials at the 25-cm depth were only found when the water table was above the 25-cm depth. Slightly upslope at the Parnell site, the water table was within 25 cm of the surface for 7 weeks during 1993; however, positive soil water potentials were not found by the tensiometers at 25 cm during this same period. This incongruity is unexplainable at this time.

Table 7
Summary of 1993^a Hydric Soil Indicator Information at the Dalton Study Site

Station	Soil Family	Weeks Piezometric Surface Within 25 cm ^b	Weeks Water Table Within 25 cm ^c	Weeks Redox Potential Below 300 mV at 25 (and 50) cm ^d	Hydric Soil Indicators ^e	A-hor. Matrix Color (depth) B-hor. Matrix Color (depth)
Buse	Fine-loamy, mixed Udothentic Haploboroll	0	0	N/A ^f	None	10YR 3/2 (0-16 cm) 2.5Y 5/3 (16-190 cm)
Forman	Fine-loamy, mixed, Udic Argiboroll	0	0	N/A ^f	None	10YR 3/1 (0-14 cm) 2.5Y 5/3 (14-200 cm)
"Bench"	Fine-loamy, mixed, Pachic Haploboroll	0	0	N/A ^f	None	10YR 2/1 (0-113 cm) 2.5Y 5/3 (113-180 cm)
Parnell	Fine, montmorillonitic, frigid, Typic Argiaquoll	7 ^g	7 ^g	8(6)	None	10YR 2/1 (0-67 cm) 10YR 3/1 (67-102 cm)
Parnell Very Poorly	Fine, montmorillonitic, Typic Argiaquoll	14	16	10(8)	None	10YR 2/1 (0-136 cm) 2.5Y 2.5/1 (136-208 cm)

^a Based on observations recorded between 31 May-14 October 1993.

^b Based on depth to piezometric surface readings from 200-cm piezometers read at 2-week intervals; number of weeks based on time period inclusive between consecutive readings all of which were above 25 cm.

^c Based on depth to water table readings from 300-cm wells read at 2-week intervals; number of weeks based on time period inclusive between consecutive readings all of which were above 25 cm.

^d Based on electrode potential readings (corrected to pH 7) from 25- (and 50-) cm platinum electrodes read at 2-week intervals; number of weeks based on time period inclusive between consecutive readings all of which were below 300 mV.

^e Categories from DRAFT of Testing Version (February 1, 1994) of Field Indicators of Saturated Hydric Soils in the United States.

^f No platinum electrode data available for this station.

^g Occurred during two or more separate periods.

Redox potentials less than 300 mV were recorded at a depth of 25 cm for the soils at the Parnell and Parnell Very Poorly sites. These low redox potentials correspond to the time when the water table was above the 25-cm depth. Redox potential steadily increased from early July through September as the water table dropped from near the surface to a depth of approximately 1 m in both the Parnell and Parnell Very Poorly soils. Consequently, periods of low redox potential were closely associated with periods of soil saturation.

Effects of soil temperature. Measurements of soil temperature at 25 cm below the soil surface indicate that soil temperatures are above 5 °C from the first week of May through mid-October. The inferred growing season for the frigid soil temperature regime (USDA Soil Conservation Service 1991) begins on the same date, but would end 2 weeks before that based on measured soil temperatures at a 25-cm depth (Table 8). Growing season estimates based on long-term air temperature data with temperature thresholds of 28 and 32 °F are within 1 to 2 weeks of the soil temperature estimates. If only the time period when soil temperature is above 5 °C at 25 cm is considered, the water table for the Parnell Very Poorly soil was above 25 cm for 8 weeks, and the water table for the Parnell soil was above 25 cm for 6 weeks. The influence of soil temperature on the onset of reducing conditions in the spring could not be determined because redox measurements were not taken until 1 May when soil temperatures were already above 5 °C and low redox potentials were already present.

Table 8
Estimates of the Growing Season at Dalton Based on Soil Temperature Measurements, the Soil Temperature Regime, and Air Temperature Data

Method	Beginning Date	Ending Date
Soil Temperature > 5 °C at 50-cm depth	1 May	15 October
Inferred from Frigid Regime	1 May	30 September
Inferred from Air Temperature Data (28 °F Threshold)	28 April	10 October
Inferred from Air Temperature Data (32 °F Threshold)	8 May	27 September

Soil morphological indicators. The Parnell and Parnell Very Poorly soils both had thick (67-137 cm), black (10YR 2/1) A horizons. The surface horizon (A1) for the Parnell Very Poorly soil is most likely postsettlement erosional sediment from the uplands when this hillslope was being used for agricultural production. Evidence for this assertion includes a clear smooth lower horizon boundary and a strongly effervescent reaction to HCl in the A1 horizon with no reaction in the A2 horizon, indicating the soil material may have eroded from the calcareous soils exposed on the upper portions of the hillslope and buried the noncalcareous surface. The transition from an A to a

B horizon is somewhat difficult to distinguish for this soil. Black matrix colors (10YR 2/1 and 2.5Y 2.5/1) extend to a depth of 208 cm, where a very dark grey (5Y 3/1) horizon with abundant dark greenish gray (5GY 4/1) crystals, snail shells, and a positive reaction to α, α' -dipyridyl is found. Prominent grayish brown (2.5Y 5/2) and light olive brown mottles begin to appear at 97 cm with the grayish brown mottles extending to 136 cm and the light olive brown mottles extending to 208 cm. The designation of an argillic horizon from 39 to 208 cm is questionable because the features described as clay films were not present when the soil was allowed to dry; they may have been moisture films on pressure faces. Thin section and particle-size analysis will provide additional insight. Unfortunately, these analyses have not been completed yet.

The soils at the Parnell and Parnell Very Poorly sites did not meet the proposed indicators for hydric soils because (a) there were no redoximorphic concentrations in the A horizon within 30 cm of the surface and (b) the mollic was thicker than 30 cm. While additional monitoring data are required before more conclusive statements can be made, these preliminary results suggest two things: (a) special consideration may be required for soils in depressional landscape positions that may have received postsettlement erosion sediment and/or (b) the restriction on the depth of the mollic horizon to 30 cm or less when considering the characteristics of the first horizon directly beneath the mollic should be reconsidered.

Due to the anomalously high rainfall during the summer of 1993, additional data must be collected in order to establish the soil water regime and the presence of wetland hydrology for the soil at the Parnell Very Poorly site. Nevertheless, the Parnell Very Poorly site represents the member of this soil catena that is subject to the longest period of saturation, and morphological comparisons with other upslope soils can indicate possible morphological changes associated with increasing duration of saturation. The following comments must be interpreted with the caveat that hydrology for these soils has not been established and that differences along the toposequence are assumed to be primarily due to differences in the duration and depth of seasonal soil saturation rather than spatial changes in the other soil-forming factors (Jenny 1941).

The soil at the unnamed site can be considered somewhat anomalous with regard to a drainage sequence of soils because it occupies a small bench on the hillslope. If one considers the hillslope sequence from upland to depression of Buse, Forman, Parnell, and Parnell Very Poorly, the following soil morphological changes were observed: (a) increase in the depth of the A horizon (this may be partly due to increased duration of saturation and partly due to deposition of erosional sediments); (b) darker surface horizon colors in the lower landscape positions ranging from 10YR 3/2 to 10YR 2/1 (Table 7); (c) decreasing chroma of the uppermost B horizon (Table 7); and (d) presence of distinct or prominent mottles (apparent redox concentrations) in a dark colored (value of 3 or less) matrix (none in Buse and Forman, 10YR 3/4 from

44 at 67 cm depth in Parnell, 2.5Y 5/4 and 2.5Y 5/2 at 97 cm depth in Parnell Very Poorly).

Apparent redox concentrations, oxidized rhizospheres, and/or redox depletions are not evident in the upper 44 cm of the soils at the landscape positions where saturated soil conditions were observed within 30 cm of the surface during 1993. Based on the February 1994 draft version of Field Indicators of Saturated Soils in the United States, there were no soil morphological features that would indicate the presence of hydric soils for the Dalton site. While subsequent years of monitoring are required to more accurately establish the hydrology for the Dalton site, preliminary results suggest that the proposed hydric soils indicators may not be effective for the soils in this landscape and modifications of the proposed hydric soil indicators would be appropriate. Postsettlement erosional deposition in this basin adds another dimension to the problem of identifying hydric soils on this site. However, the possibility for the deposition of postsettlement erosional sediments in depressional basins exists throughout many agricultural landscapes of the midwestern United States.

Preliminary Conclusions

Soil redoximorphic features are thought to develop over hundreds to thousands of years and, therefore, provide an indicator of long-term soil hydrology. As such, reliable associations between soil morphological features and 1 or 2 years of observational data on soil hydrology cannot be made because the range of hydrologic variability has not been established. Because rainfall is a crucial variable in this study, the response of soil hydrology to a range of rainfall conditions must be observed before meaningful conclusions can be formulated. Based on the limited amount of data collected to date, numerous trends that appear to agree with general understanding of soil genesis in wet environments have been observed. The following statements must be taken with caution and with the realization that they represent preliminary findings and are still speculative.

The identification of reliable redoximorphic features for Mollisol landscapes is confounded by the accumulation of organic matter in the upper portion of the soil profile derived from current and/or past prairie vegetation. This characteristic accumulation of organic matter appears to mask many of the redoximorphic features that may be present in soil profiles formed under other circumstances (non-Mollisols). The most consistently observed change in soil profile morphology from upland to depressional positions is a change in the color of the soil horizon immediately beneath the mollic epipedon to a lower chroma compared with the same soil horizon in uplands. The following trends were observed in soil morphology from upland to depressional portions of the landscape:

Thief River Falls

- Increased accumulation of organic materials on the mineral soil surface.
- Redoximorphic concentrations in the A horizon associated with apparent oxidized rhizospheres.
- Low chroma (≤ 2) matrix for the uppermost B horizon with prominent strong brown (7.5YR 4/4 to 4/6) mottles (apparent redox concentrations).

Faribault

- Decreased chroma of the surface soil horizon (2 to 0).
- Increasing thickness of the A horizon (24 to 77 cm).
- Decreasing chroma of the upper B horizon (4 to 1).
- Prominent, strong brown (7.5YR 4/6) mottles (apparent oxidized rhizospheres in the A horizon with a matrix chroma of 1 or less):
 - From 0 to 20 cm for Nerstrand Poorly (Toeslope).
 - From 25 to 63 cm for Epsom (Depression).

Dalton

- Increased depth of the A horizon. This may be partly due to increased duration of saturation and partly due to deposition of erosional sediments.
- Darker surface horizon colors in the lower landscape positions (10YR 2/1 versus 10YR 3/2).
- Decreasing chroma of the uppermost B horizon.
- Presence of distinct or prominent mottles in a dark colored (value of 3 or less), matrix:
 - None in uplands.
 - 10YR 3/4 from 44 at 67-cm depth for toeslope position.
 - 2.5Y 5/4 and 2.5Y 5/2 at 97-cm depth in depression.

These preliminary observations suggest that clear redoximorphic features may not be present in the upper 30 cm of the soil profile, even if a saturated, reducing environment exists above this depth. Clear(er) morphologic clues may only be found by examining the soil profile to a greater depth and comparing soil profile characteristics across a landscape catena. Additional monitoring data are needed to confirm this observation. Observations at the Dalton and Faribault sites also suggest that the accumulation of postsettlement erosional sediments in the depressional portions of the landscape may further confound the identification of hydric soil conditions.

References

- Hobbs, H. C., and Goebel, J. E. (1982). Geologic map of Minnesota: Quaternary geology. University of Minnesota, Minnesota Geological Survey, St. Paul, MN.
- Jenny, H. (1941). *Factors of soil formation—a system of quantitative pedology*. McGraw-Hill, New York.
- Richardson, J. L., Wilding, L. P., and Daniels, R. B. (1992). "Recharge and discharge of groundwater in aquic conditions illustrated with flownet analysis," *Geoderma* 53, 65-78.
- U.S. Department of Agriculture Soil Conservation Service. (1991). *Hydric soils of the United States*. U.S. Department of Agriculture Miscellaneous Publication 1491.
- Wright, H. E. (1972). "Physiography of Minnesota." *Geology of Minnesota: A centennial volume*. P. K. Sims and G. B. Morey, ed., University of Minnesota, Minnesota Geological Survey, St. Paul, MN.

6 Preliminary Investigations of Hydric Soil Hydrology and Morphology in North Dakota¹

Description of the Study Areas

Wet soil monitoring project sites in North Dakota are located near Langdon (Cavalier County), Noonan (Divide County), and McLeod (Ransom County). All sites possess a continental climate (National Oceanic and Atmospheric Administration 1974), and landforms at all sites were modified by the last Wisconsin glacialiation about ten to twelve thousand years ago (Blumle 1991).

Langdon

Location, climate, and geomorphic setting. The Langdon site is located in northeastern North Dakota about 24 km south of the international border and 80 km west of the Minnesota border (48° 15' N, 98° 20' W). The site is on the Langdon Agricultural Experiment Station and is cropped to small grains and sunflowers.

Langdon has a cool, dry subhumid climate (Thorntwaite 1948) with annual average precipitation of about 45 cm. The growing season lasts an average of 102 days, with about 26 cm of rainfall occurring during this period (National Oceanic and Atmospheric Administration 1974).

The site lies in the Drift Prairie of the Central Lowlands physiographic province (Fenneman 1931). Most of the site is low relief ground moraine of

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the Pleistocene Coleharbor Group (Arndt 1975). An intermittent stream flows through the southern end of the site and has deposited modern alluvium over the till. Cretaceous Pierre Shale underlies the locality at depths of less than 15 m (Arndt 1975), but subcrops at substantially shallower depths at the study site. The siliceous shale is hard, gray, and contains occasional thin bentonite beds.

Soils information. The till at this site is generally calcareous loam or clay loam with occasional cobbles and sandy strata scattered throughout. Shale fragments are commonly encountered, indicative of the near-surface Pierre Formation. Many area soils are saline and/or sodic (Simmons and Moos 1990). Sodium and magnesium sulfates derived from the smectitic shale are likely responsible for the soil salinity. The five-soil monitoring transects described and sampled for laboratory characterization during the summer of 1993 follow a catena commonly found in the Langdon area (Figure 1).

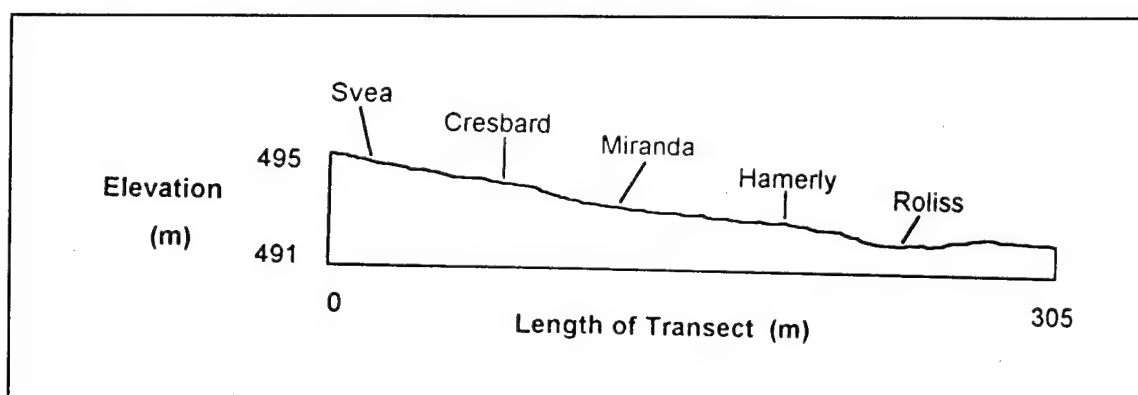


Figure 1. Generalized catena at Langdon site

Svea. The highest pedon was classified as a Fine-loamy, frigid, Cumulic Endoaquoll, although it is believed that pedon resembles a moderately well-drained, moderately slowly permeable Fine-loamy, frigid, Pachic Udic Haploboroll for reasons explained in the Results and Discussion section. The pedon most closely fits the Svea series, which is extensive in the county. The profile contains coarser materials in the lower C horizons than is typical for Svea, and occupies a gentle upland swale at the north end of the transect.

Cresbard. The soil found on a gently sloping backslope south of the Svea is a moderately well-drained, slowly permeable, Fine, montmorillonitic Glosic Udic Natriboroll. The described profile falls within the range of the Cresbard series, although it contains coarser materials in the lower C horizons than typical.

Miranda. A somewhat poorly drained, very slowly permeable, Fine-loamy, mixed Leptic Natriboroll was described on a nearly level footslope at the center of the site. The profile closely resembles the Miranda series, although its natric horizon contains weaker structure than is typical.

Hamerly. The Hamerly series closely resembles the somewhat poorly drained, moderately slowly permeable, Fine-loamy, frigid Aeric Calciaquoll found on a flat bordering the intermittent stream. This profile contained coarser layers than typical for the series in its C horizons.

Roliss. The lowest soil at the site is a poorly drained, moderately slowly permeable, Fine-loamy, mixed (calcareous), frigid Cumulic Endoaquoll. This profile is adjacent to the intermittent stream, and consists of alluvium over till. The Roliss series description requires lacustrine sediments over till and a lake plain setting, but is the most similar to the sampled soil. Other soils in the county resembling this profile have been correlated as Roliss in the past (Simmons and Moos 1990).

Water sources and hydrodynamics. Rainfall and melting snow are the water sources for the Svea, Cresbard, and Miranda sites. Significant perching and lateral redistribution of water at these sites appear to occur due to the shallow depth to shale. Past investigations near the area suggest bedrock depths of 10 to 15 ft. Since the precipitation/evapotranspiration (P/E) ratio is less than one, unsaturated upward flow of soil water frequently occurs. Natric horizon development and salt accumulation in the Cresbard and Miranda pedons illustrate this process. Water table depth at the Svea site is generally lower, retarding the accumulation of salts.

Direct precipitation is also a water source for the Hamerly and Roliss pedons, although it is supplemented by inflow from an intermittent stream that has a watershed of approximately 715 ha upstream from the site. The shale does not exert a strong control on water flow at the Hamerly and Roliss sites due to the thickness of the stream alluvium. Rapid influx of water into the Hamerly characterization pit from its very permeable lower C horizons suggests this sandy stratum is extensive and transmits water from a considerable distance upslope. Similar sandy strata were found in other excavations along the monitoring transect, although none carried as large a water volume. These strata appear to be important conduits for water redistribution on the monitoring site landscape. The Hamerly and Roliss pedons are subject to brief flooding after periods of heavy rain or rapid snowmelt.

Noonan

Location and climate. Two sites are located near Noonan in northwestern North Dakota. Both sites are about 80 km east of the Montana border. The Noonan North site is 5 km south of the international border (48° 57' N, 102° 59' W), and the Noonan South site is about 16 km south of the border (48° 51' N, 103° 2' W).

The Noonan area has a cool climate, and lies on the boundary between the dry subhumid and semiarid moisture regions (Thorntwaite 1948). Precipitation averages about 38 cm annually, with about 24 cm falling during the 117-day growing season (National Oceanic and Atmospheric Administration 1974).

South Site

Geomorphic setting. Noonan South lies on the Plumer-Alkabo Phase of dead-ice moraine in the Missouri Coteau (Hansen 1967). The area is characterized by high relief hummocky till with nonintegrated drainage. This landscape formed when blocks of stagnant ice buried by thick deposits of supraglacial drift slowly melted, and saturated glacial drift slumped into the resulting depressions (Bluemle 1991). Local relief of up to 35 m is common, with numerous wetlands occupying the depressions. Thirty-five to seventy meters of glacial drift overlie Paleocene shales, siltstones, and lignite of the Tongue River Formation in the area (Armstrong 1967).

The site is located on a wave-cut bench of a semipermanent wetland that is separated from the surrounding upland by a 3- to 4-m-high escarpment. Wave action during a high-water phase of the wetland developed these features by steepening and undermining its shoreline (Sloan 1972; Aronow 1982). The wave action resulted in stratification of nearshore deposits and formation of a small beach (Aronow 1982; Arndt and Richardson 1988). Wetland vegetation is found around the site, although the area has been cropped to oats during very dry periods in the past.

The soils along the monitoring transect were strongly modified by wave action and fluctuating water levels in the wetland basin. The two soils described and sampled for laboratory characterization during the summer of 1992 developed in shoreline deposits, till, and local alluvium derived from till.

Roliss. A Roliss-like pedon was encountered at this site, although its landscape position was out of the series range. The poorly drained, moderately slowly permeable, Fine-loamy, mixed (calcareous), frigid Typic Endoaquoll lies on a gentle footslope directly beneath the wave-cut scarp. The profile described is representative for a large portion of the site (Figure 2).

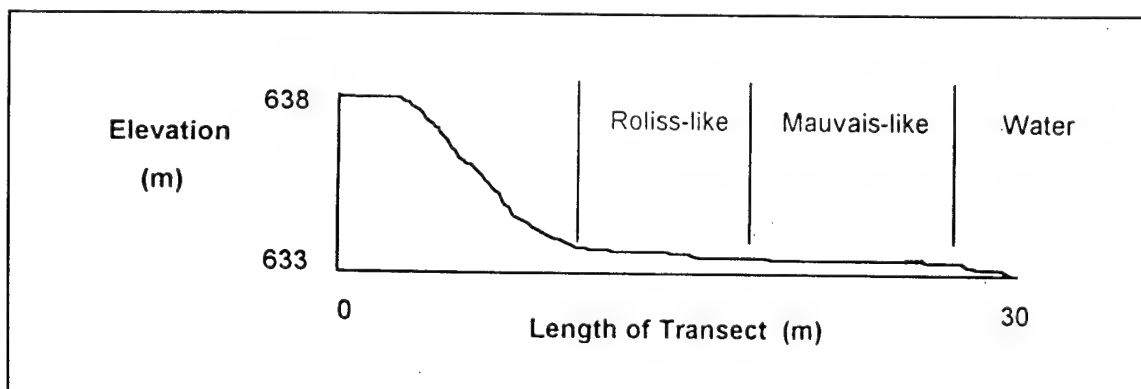


Figure 2. Generalized catena at Noonan South site

Mauvais Taxadjunct. The soils nearest the wetland at the site are poorly drained, moderately rapidly permeable, Coarse-loamy over sandy or sandy skeletal, mixed (calcareous), frigid, Typic Endoaquents. The most similar series in North Dakota is the Mauvais, which are Fine-loamy, mixed (calcareous), frigid Aeris Endoaquents. The profile described represents the soils found on the nearly level shoreline of the wetland (Figure 2).

Water sources and hydrodynamics. The monitoring transect is adjacent to a 2-ha prairie pothole wetland with a watershed of approximately 36 ha. Some overland runoff into the wetland occurs after heavy rains, but most of the runoff occurs during spring snowmelt. Precipitation fluctuations occasionally cause the wetland to dry up completely, but it usually contains some water throughout the year.¹ The P/E ratio at both Noonan sites is < 1, leading to significant upward movement of water in the profiles during dry periods. Bk horizon development in the Roliss pedon is a result of this process, with edge-focused discharge around the wetland fringe concentrating carbonates in the Roliss landscape position.

North Site

Geomorphic setting. Noonan North lies in the Drift Prairie on a ground moraine deposited during the Long Creek Phase of glaciation (Hansen 1967). The monitoring transect extends north from a closed depression to the adjacent upland. Local relief is less than 3 m, and drift thickness over Paleocene bedrock is generally less than 15 m. A thinning margin of glacier ice stagnated in this area, releasing meltwater that drained to the southeast (Hansen 1967). The meltwater formed large outwash plains and meltwater channels west and south of the site, and also reworked much of the ground moraine. Downcutting of north-flowing streams on the Coteau and subsequent deposition of their sediment loads as a veneer over the ground moraine also modified surficial drift (Hansen 1967). The site has been cropped to small grains and sunflowers in the past, but currently is seeded to grass as part of the Conservation Reserve Program.

Soils in the site area are commonly saline and/or sodic. Redistribution and concentration of bedrock-derived sodium sulfates through subsurface water flow from the south is the suspected cause of these properties (Armstrong 1967). Five soils were described and sampled for laboratory characterization during the summer of 1992. Soils on the catena are derived from calcareous till overlain by silty glaciofluvial deposits, and range from poorly to moderately well drained (Figure 3).

Fulda. The lowest soil on the catena occupies a concave basin and is a poorly drained, slowly permeable, Fine, montmorillonitic, frigid Vertic Endoaquoll. The Fulda series currently consists of Fine, montmorillonitic, frigid

¹ Personal Communication, 1993, T. Dhuyvetter, Dairy Farmer, Divide Co., ND.

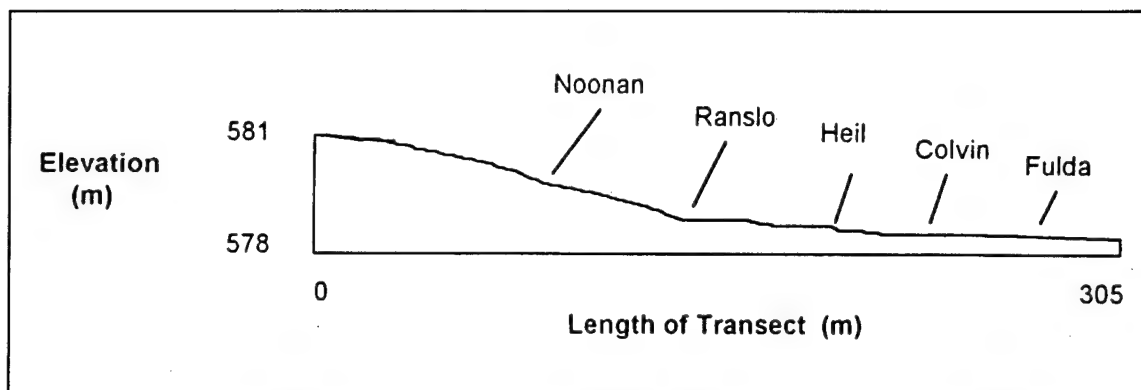


Figure 3. Generalized catena at Noonan North site

Typic Endoaquolls, but may be reclassified to Vertic Endoaquolls in the near future.

Colvin Taxadjunct. This poorly drained, moderately slowly permeable pedon is classified as a Fine-silty, mixed, frigid Typic Endoaquept. The epipedon was too thin to meet mollic criteria, but otherwise the pedon is very similar to the Colvin series (Fine-silty, frigid Typic Calciaquolls). This soil occurs at nearly the same elevation as Fulda in the wetland basin, although Fulda lies in a microlow. The Colvin Taxadjunct profile was described on a microhigh.

Heil Taxadjunct. This pedon, as sampled, is classified as a Fine-loamy, mixed, frigid Typic Endoaquoll. The poorly drained, very slowly permeable profile has morphological and chemical characteristics indicating the presence of sodium, however, so this soil has been taxadjuncted to the Heil series (Fine, montmorillonitic, frigid Typic Natraquolls). The soil is found on a flat just above the Fulda and Colvin profiles.

Ranslo Taxadjunct. This somewhat poorly drained, slowly permeable pedon lies on a gentle footslope above the Heil Taxadjunct pedon, and classifies as a Fine-loamy, mixed, frigid Vertic Endoaquoll. The pedon appeared to be sodium-affected and nearly meets natric criteria according to laboratory data, leading one to taxadjunct this soil to the Ranslo series (Fine, montmorillonitic, frigid Typic Natraquolls). The profile's upland landscape position differs significantly from its usual position on floodplains and low terraces, however.

Noonan. The Noonan series consists of Fine-loamy, mixed Typic Natriborolls. The moderately well-drained, slowly permeable profile occupies a backslope at the northern end of the site, and was considered outside the wetland basin.

Water sources and hydrodynamics. The monitoring transect lies in and north of a shallow 9-ha wetland basin with approximately a 110-ha watershed.

Since the relief of the watershed is very gentle, much of the precipitation falling upon it infiltrates before reaching the basin overland. Surface ponding of water has been observed on the natric soils of the site after heavy rains, however, which may contribute significantly to basin recharge. The water ponds above the very slowly permeable Btn horizons and flows laterally downslope. Regional groundwater flows northerly along the Paleocene bedrock from the topographically higher Missouri Coteau south of the site into Canada. Water ponds around the Fulda, Colvin, and Heil pedons occasionally after snowmelt and periods of heavy rain.

McLeod

Location, climate, and geomorphic setting. The McLeod site is located at the western margin of the Sheyenne delta physiographic subprovince about 6 km east of the Sheyenne River in the east-central part of Ransom County (46° 26' N, 97° 24' W). Surficial sediments consist of well-sorted medium to fine-grained sands deposited by the ancestral Sheyenne River as it emptied into Glacial Lake Agassiz. The sediments have been modified by wind during the Holocene to form low-relief dunes (Harris 1987). Locally, dune sediments exhibit obscure bedding and indistinct cross-stratification. Weakly developed paleosols are common (Thompson and Joos 1975) and have often been observed at higher elevations of the study site. Currently, the surface is stabilized by rangeland vegetation, although active blowouts can be observed in the area. At lower elevations in the study site, numerous lenses of coarse sand interbedded with thin strata of silt loam and clay loam have been observed at depths of 0.75 to 1.5 m. These variations in particle size likely reflect fluvial reworking of the deltaic sediments.

The McLeod site has a cool, dry subhumid climate (Thorntwaite 1948) with 49 cm of average annual precipitation (National Oceanic and Atmospheric Administration 1974). The growing season averages 130 days in length, with about 41 cm of rainfall during this period (Thompson and Joos 1975).

Soil information. Four pedons were selected on backslope, footslope, and toeslope positions of a typical catena in the area (Figure 4). All of the soils are Mollisols, but variations in vegetation and drainage exert a dominant effect on thickness and color of the mollic epipedon. The Hecla and Ulen sites support true prairie vegetation communities, while Fossum and Venlo sites support sedge meadow community types. Drainage classes range from moderately well to very poorly drained.

Hecla. The landscape position of this soil was initially thought to be consistent with landscapes described in the Hecla official series description (Sandy, mixed Aquic Haploborolls). However, morphologic criteria (prominent redox features in the A2 horizon) indicate that this soil may be hydric.

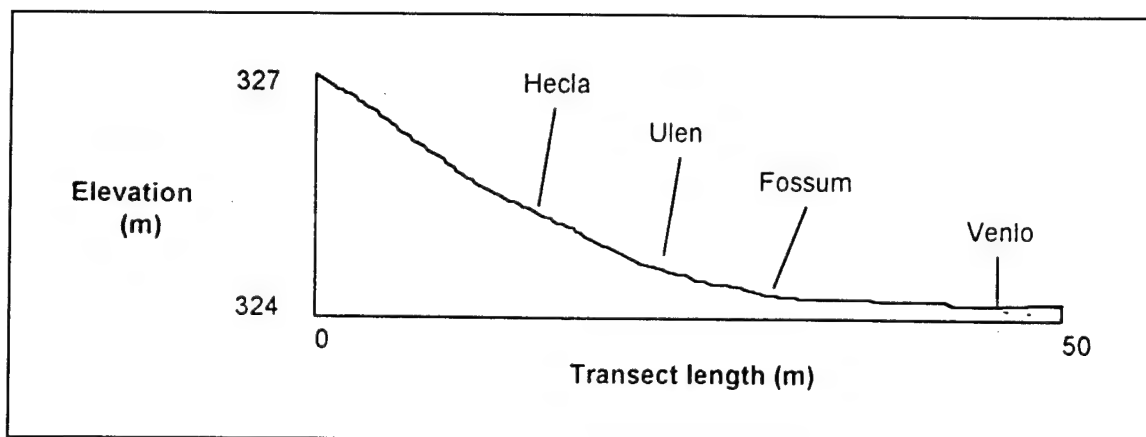


Figure 4. Generalized catena at McLeod site

Ulen. This soil was initially sampled as a Ulen soil (somewhat poorly drained, rapidly permeable, Sandy, mixed Aerice Calciaquolls); morphologic and laboratory evidence do not support this premise. Calcium carbonate content in the Bk horizons does not meet calcic criteria. Prominent redox concentrations and a weakly calcareous solum suggest classification as a Sandy, mixed (calcareous) frigid Typic Endoaquoll.

Hamar. The Hamar soil is a poorly drained, rapidly permeable, Sandy, mixed, frigid Typic Haplaquoll. This soil has a calcareous surface, which is out of the Hamar series range.

Venlo Taxadjunct. The Venlo soil is a very poorly drained, rapidly permeable, Sandy, mixed, frigid Typic Haplaquoll, and closely resembles the Sandy over loamy, mixed, frigid Typic Endoaquoll found at this site.

Water sources and hydrodynamics. The catena at the McLeod site is strongly affected by its proximity to the unconfined Sheyenne Delta aquifer (SDA). This aquifer extends below about 1,950 km² in Richland, Cass, Sargent, and Ransom counties (Armstrong 1982). Water chemistry in the SDA is classified as a calcium-bicarbonate type. Ion concentrations in the water are relatively dilute due to substantial recharge from precipitation and snowmelt through the permeable sandy soils (Downey and Paulson 1974). Mean total dissolved solids from 28 wells tested in the SDA was 386 mg/L (electrical conductivity = 0.60 dS/m), and sodium adsorption ratio ranges from 0.1 to 6.4 (Armstrong 1982).

Depth to the water table is usually very shallow in the spring following snowmelt and thawing of the frost layer. Spring precipitation also contributes to higher water levels, although levels drop sharply as vegetation growth intensifies during late spring and early summer (Armstrong 1982). Larger than average rainfall events can initiate formation of small ponds in depressional areas such as those formed during June and July of 1993. Reduction of

precipitation in the autumn initiates a gradual decline in water table depth through the winter, until spring recharge resumes the annual cycle.

Methods

Monitoring locations

One instrument cluster was located at each soil described at the Langdon, Noonan North, and McLeod sites. The clusters were placed at the same elevation and 1.5 to 4.5 m from where the soil characterization pits were excavated. This distance was thought to minimize the effects of excavation on instrument readings while still providing a representative example of the soil at each site. Two instrument clusters per soil were installed at Noonan South since each soil covers a large portion of the site area. The Roliss clusters were spaced about 2 m apart, with one at the base of the wave-cut scarp and the other downslope. The Mauvais clusters are about 1 m apart, with one downslope from the other.

Monitoring procedures

Precipitation, air temperature, water table level, hydraulic head, soil temperature, redox potential, volumetric moisture, matric potential, and presence of ferrous iron were measured at the monitoring sites. Water table and hydraulic head data were collected from wells and piezometers constructed with 5-cm-diam polyvinyl chloride pipe screened for the final 60 cm of its depth. Soil temperature was measured with dual thermocouples at each depth by a digital thermometer or datalogger. Redox potential was determined using platinum electrodes read with a voltmeter and an Ag-AgCl reference electrode. Volumetric moisture was measured in situ with a neutron probe, and matric potential was determined with tensiometers read with a digital pressure transducer. Alpha, alpha'-dipyridyl was used to detect ferrous iron. Types and depths of instrumentation vary from site to site (Table 1). Instruments were monitored every 2 weeks, although some piezometers at the sites are equipped with automatic recorders that provide continuous records of hydraulic head changes over time.

Precipitation records

Langdon. Precipitation the last 3 years has fluctuated significantly from the 97-year average of 46.3 cm. Precipitation in 1991 was below average early and late in the year, but was 11.2 cm above average due to excess growing season rainfall. Only May, July, November, and December precipitation was above average in 1992, and the year ended 8.9 cm below average. The below average trend continued for the first 4 months of 1993, but precipitation during May, June, and July alone exceeded the annual average. Very high

Table 1
Instrumentation Depths (cm) at the Monitoring Sites

Site	Soil Thermocouples	Well	Piezometer	Platinum Electrodes	Neutron Probe Readings	Tensiometer
<i>Langdon</i>						
Svea	10, 25, 50	500	360	-- ¹	15, 30, 45	--
Cresbard	10, 25, 50	500	360	25, 50	15, 30, 45	--
Miranda	10, 25, 50	500	360	25, 50	15, 30, 45	--
Hamerly	10, 25, 50	500	500	25, 50	--	50
Roliss	10, 25, 50	500	500	25, 50	--	50
<i>Noonan North</i>						
Noonan	10, 25, 50	500	500	--	--	--
Ranslo	10, 25, 50	500	500	25, 50	--	--
Heil	10, 25, 50	500	500	25, 50	--	--
Colvin	10, 25, 50	500	500	25, 50	--	--
Fulda	10, 25, 50	500	500	25, 50	--	--
<i>Noonan South</i>						
Roliss 1	10, 25, 50	300	300	25, 50	--	50
Roliss 2	10, 25, 50	300	300	25, 50	--	50
Mauvais1	10, 25, 50	300	300	25, 50	--	50
Mauvais 2	10, 25, 50	300	300	25, 50	--	50
<i>McLeod</i>						
Hecla	--	*2	--	--	15, 30, 45	--
Ulen	5, 10, 15, 30, 50	230	430	*	15, 30, 45	15, 30, 45
Fossum	5, 10, 15, 30, 50	160	--	*	15, 30, 45	15, 30, 45
Venlo	5, 10, 15, 30, 50	160	360	*	15, 30, 45	15, 30, 45
¹ Not installed or installed at depths below 50 cm. ² To be installed in 1994.						

water tables were noted throughout the monitoring transect, with the Roliss and Hamerly sites flooded during parts of June and July. Precipitation was below average from August through December, but the year ended with a 13.1-cm excess.

Noonan. Noonan lies between long-established weather stations in Crosby and Bowbells. Average annual precipitation for Noonan interpolated from the weather station data is about 37 cm. A recently established weather station in nearby Columbus has recorded precipitation data for the past 3 years. Precipitation in 1991 totaled 45.8 cm, with most of the excess falling during spring and early summer. Dry conditions existed in 1992, and the year ended

5.5 cm below average. Precipitation during June, July, and August 1993 exceeded the annual average, and the year closed over 20 cm above average.

Local water table elevations were drawn down considerably during the dry years of the late 1980s. The water table has rebounded somewhat, although levels remained 3 m or more below the surface during most of 1993.

McLeod. Monthly precipitation at the McLeod site has varied markedly from the 30-year average for all but the midwinter months since the site was selected. Calendar year 1991 had roughly average precipitation, but April and September were very wet, and July and August were drier than average. During 1992, spring precipitation was about average until June when monthly rainfall was greater than twice the 30-year average. July was very dry, but August rainfall was over 3 cm greater than average. Fall and early winter of 1992 were drier than average. The greatest monthly deviations from the 30-year average were monitored in 1993; rainfall from May through July was over 85 percent of the yearly total. The wet summer was followed by the driest fall monitored since the rain gauge was installed at the study site in June of 1990.

Groundwater levels have increased steadily as a significant amount of excess precipitation has recharged the water table during the period 1990-93. In 1993, there were 19 precipitation events of greater than 1 cm, and temporary wetland areas increased markedly. Water table elevations as measured in June reflect increases of about 0.5 m each year since 1991 for a transect of six wells located adjacent to the McLeod catena. The sedge meadow at the Venlo monitoring site was dry from 1990 through 1992. In May of 1993, a pond formed in this meadow that remained into winter and spring of 1994, and is currently increasing. These observations suggest a return to hydrologic equilibrium following the drought of the late 1980s for the McLeod area.

Results and Discussion

Soil saturation and reduction

Langdon. Heavy rains in June and July of 1993 caused rapid rises in water table levels throughout the monitoring transect. The water table at the Roliss site was less than 30 cm below the soil surface from mid-June until the end of August. Despite saturation for over 2 months, reducing conditions from 25 to 50 cm were recorded only during August (Table 2). Alpha, alpha'-dipyridyl failed to give a positive reaction for ferrous iron at either the 25- or 50-cm depth. This lag in reducing conditions may be in part due to oxygenated water flow through the stratified upper horizons of the Roliss pedon. The water source is the nearby intermittent stream, which flowed during most of June and July. In addition, high pH values in the Roliss may have retarded reduction to some degree. No reducing conditions at all were

Table 2
Status of Soil Water and Redox Potential in the Roliss Soil - 1993

Measurement	Date				
	8/3	8/19	9/2	9/17	10/17
Water Level, cm below surface	20	23	37	64	86
Water Tension at 50 cm, mbar	31.7	13.7	20.7	-1.3	-35.3
Eh at 25 cm, mV	169	-74	544	548	567
Eh at 50 cm, mV	488	192	285	511	601

noted in other Langdon soils, although the lack of organic matter for a microbial energy source in deeper saturated zones of these soils may have been responsible for their oxidizing conditions.

The frequent precipitation and high water tables of 1993 at Langdon kept the soils moist during the entire growing season and did not allow us to observe soil water tensions greater than field capacity. Drier conditions in the future will allow us to estimate capillary fringe thickness. Conclusions about the seasonal timing of reduction and anaerobiosis at Langdon can be better made after observing site readings during a year with more average climate.

Noonan. Although above average precipitation occurred in the Noonan area during 1993, water table levels remained at least 3 m below the surface at both the north and south sites. The prolonged dry spell during the late 1980s lowered water tables considerably in the entire area. Little can be concluded about reduction and anaerobiosis in this area until water tables rebound to average elevations.

McLeod. The four soils at the McLeod site are strongly affected by shallow depth to groundwater. Duration of saturation for these soils can be evaluated using soil moisture records taken approximately biweekly during the growing season since July 1990. These records of volumetric moisture were combined with soil moisture characteristic curve data obtained for the Hamar, Ulen, and Hecla soils in 1992. Volumetric moisture data for the Venlo soil was coupled to a characteristic curve determined for a soil between the Venlo and Hamar sites. Extremely wet conditions and ponded water prevented installation of platinum electrodes at the McLeod site, thus Eh data are presently unavailable.

The Venlo soil profile was consistently wetter than the tenth-bar moisture content as determined in the laboratory. Water content was in fact much higher than tenth-bar moisture for almost all depths during the recording period (Figure 5). It appears that the entire Venlo profile was at or near saturation for much of the 1991 field season, even though 1991 was a relatively dry year at the McLeod site.

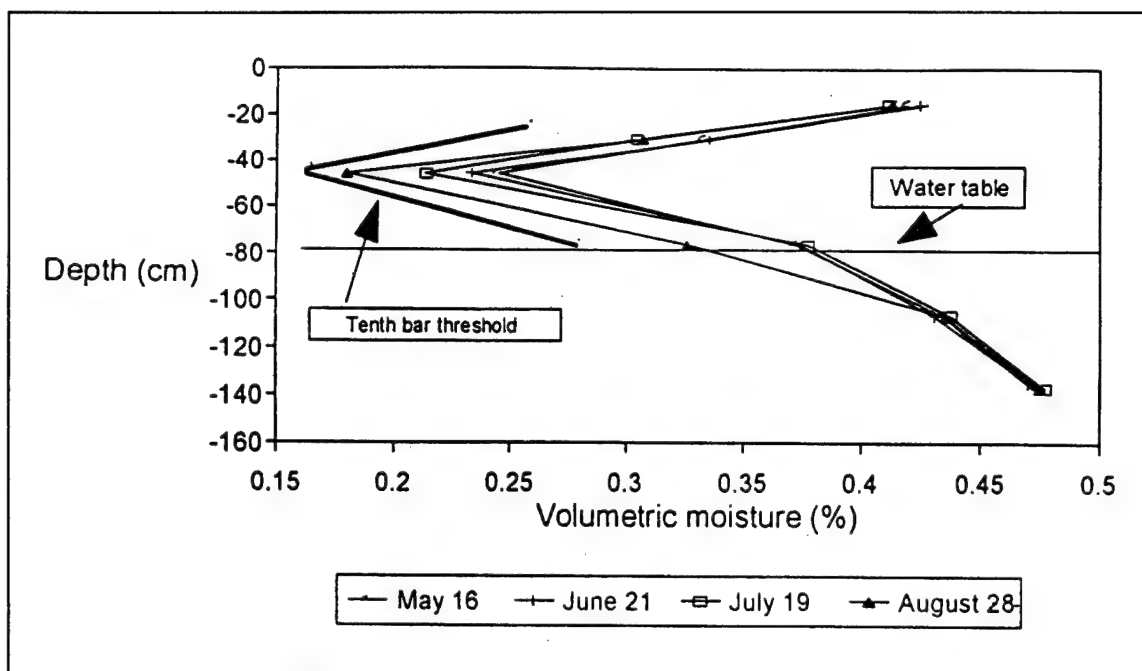


Figure 5. Soil moisture changes with depth for Venlo soil in 1991

Soil water tensions at the Ulen site were generally less than one-tenth bar throughout the recording period, although July and August readings at the 30-cm depth were somewhat higher (Figure 6). The markedly higher soil

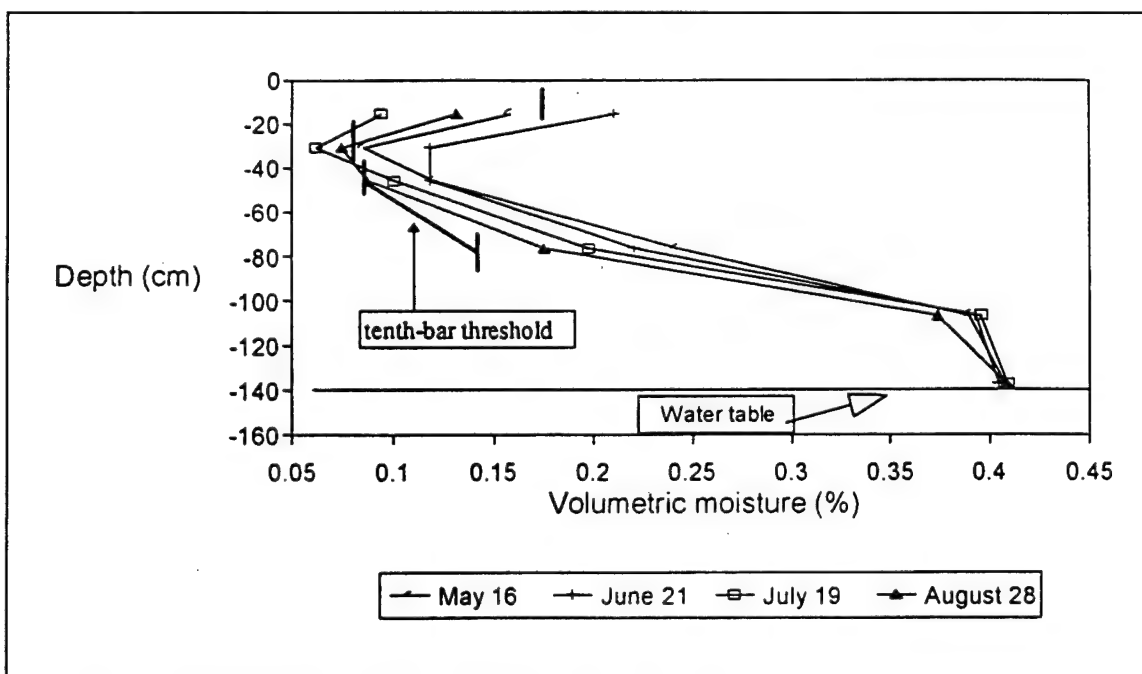


Figure 6. Soil moisture changes with depth for Ulen soil in 1991

water contents at the 76- and 107-cm recording depths for all the reading dates seem to indicate that these areas are within the capillary fringe and suggest that the upper boundary of the capillary fringe existed somewhere between 30 and 76 cm during this time period. The Hamar soil is about 3 m from the Ulen soil on the monitoring transect and has similar moisture contents and water table elevations.

The Hecla soil is the moderately well-drained member of the McLeod catena and remained drier than one-tenth bar at its three upper monitoring depths for a majority of the field season (Figure 7). Sand contents greater than 90 percent below the Hecla's surface horizon explain the low moisture contents. The water table was over 160 cm below the soil surface during this time, and the significant reductions in water content at the 107-cm depth suggest that it was above the capillary fringe during the monitoring period.

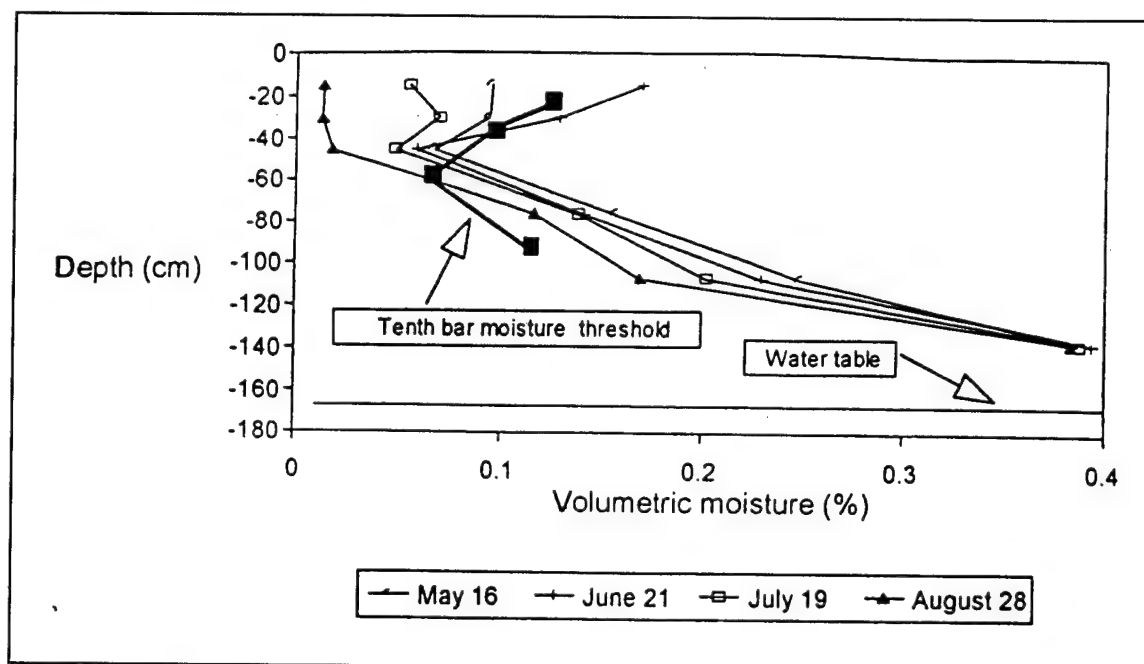


Figure 7. Soil moisture changes with depth for Hecla soil in 1991

Conclusions regarding saturated conditions in these soils are tentative given the instrumentation existing at the McLeod site in 1991-1992. Recognition of the saturated zones will be considerably improved as a result of wells installed along the monitoring transect in 1993. Elevations of the neutron probe access tube monitoring depths for 11 sites on the McLeod catena can be referenced to groundwater elevation as of July 1993 (Figure 8). Soil moisture monitoring has been done on 15- or 30-cm intervals, but this interval may be reduced to refine the extent of the capillary fringe.

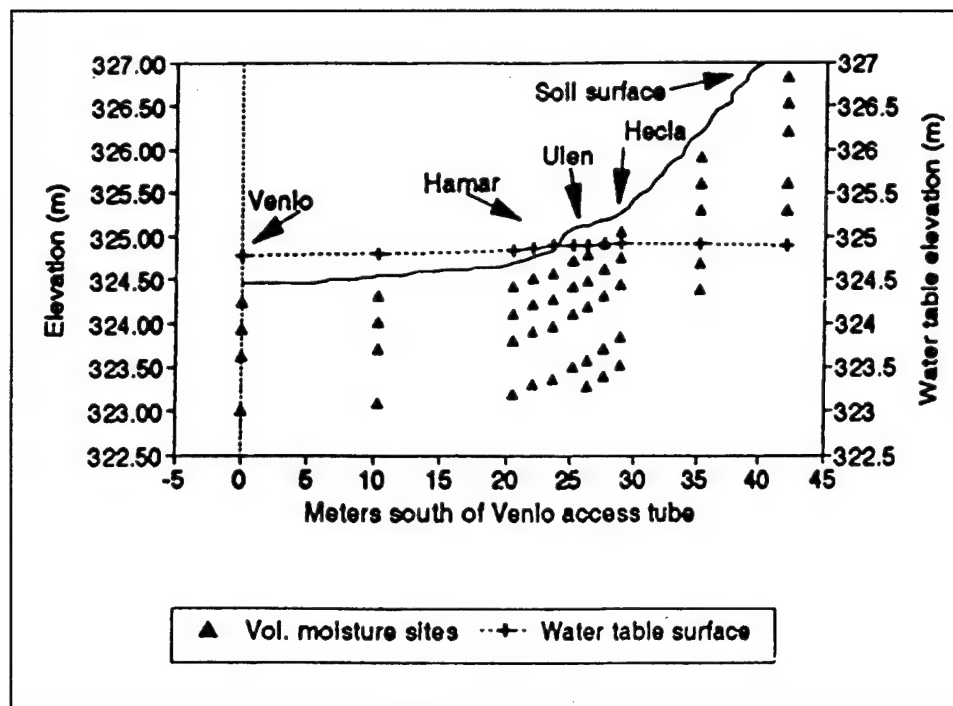


Figure 8. Cross-sectional view of McLeod soil monitoring sites

Effects of soil temperature

The brief period of reducing conditions observed at the Langdon site and lack of data at the Noonan and McLeod sites does not allow forming definitive conclusions about the effect of soil temperature on the timing of anaerobiosis and reduction. The season of soil microbiological activity is speculated to vary somewhat from generally accepted growing season dates. Small grains in the Northern Great Plains are planted and will germinate in late April and early May when soil temperatures in the seeding zone are about 5 °C. Temperatures colder than 5 °C are common during this time period at depths from 10 to 50 cm, particularly in wet, low-lying areas after a winter with little snow cover. Layers of frozen soil are commonly found in wetlands until late May or early June in this region. Conversely, killing frosts in mid- to late September are relatively frequent in North Dakota. Temperatures are often quite warm during the subsequent "Indian Summer," and soil temperatures will remain favorable for microbiological activity through October. In short, about a 1-month lag time may be a rough estimate when comparing the soil microbiological growing season with growing seasons based on soil temperature regimes or air temperature thresholds in North Dakota.

Identifying hydric soils

Langdon. The Roliss is the only soil at the site included in the hydric soils list. The Roliss mollic epipedon extends to 62 cm and has chromas of 1 or less throughout. The Bk horizon directly below the mollic epipedon has a hue of 2.5Y, a value of greater than 4, and redoximorphic features, which places this soil in the aquic moisture regime (Soil Survey Staff 1992). If this soil lacked redoximorphic features with chromas of 2 or less above 100 cm and the chroma of the Bk horizon was 3 or more, it would not be hydric. Aquic condition requirements between 40 and 50 cm are satisfied for Roliss by its poorly drained status and its apparent water table of 15 cm above to 90 cm below the surface for the period April through July (Soil Survey Staff 1987). Evapotranspirative discharge concentrates soluble salts in the Roliss Aky and Ak horizons by unsaturated flow from the shallow water table.

The Hamerly soil has an aquic moisture regime due to its calcic horizon within 40 cm of the surface. Hamerly has an apparent water table 60 to 120 cm below the surface from September through June (Soil Survey Staff 1987), but this is not close enough to the surface to satisfy hydric criteria (U.S. Department of Agriculture (USDA) Soil Conservation Service 1991). Soluble salts are concentrated in the Hamerly's Ap, Bky1, and Bky2 horizons through evapotranspiration as in the Roliss soil. Hamerly is an Aeric Calciaquoll since part of the profile above 75 cm has a chroma greater than 2. Typic Calciaquolls, which are commonly encountered in this area, are generally considered poorly or very poorly drained and hydric. In contrast to Aeric Calciaquolls, Typic Calciaquolls have chromas of 2 or less, hues 2.5Y or yellower, and/or redox concentrations throughout their upper 75 cm or directly below their mollic epipedons (Soil Survey Staff 1992).

The Svea, Cresbard, and Miranda soils have apparent water tables deeper than 60 cm throughout the year (Soil Survey Staff 1987) and are in upland landscape positions. They are not considered hydric soils under current criteria (USDA Soil Conservation Service 1991).

Noonan South. Both the Roliss and Mauvais soils at this site meet USDA Soil Conservation Service (1991) hydric soil criteria. The Roliss soil has an apparent water table from 15 cm above to 90 cm below the surface from April through July (Soil Survey Staff 1987). The Roliss profile has a 5Y 4/2 color and redox concentrations with chromas of 1 or less underlying the mollic epipedon in the Bkg1 horizon, placing this soil in the aquic moisture regime. If the Bkg1 horizon had a chroma of 4 or more, and no redoximorphic features with chromas of 2 or less were present above 100 cm, this soil would not be hydric. The 11-cm-thick organic horizon at the soil surface is suspected to be within the capillary fringe. The accumulation of organic matter is indicative of frequent wetness, which retards both oxidation and microbial decay.

The Mauvais soil qualifies for an aquic moisture regime since the zone between 40 and 50 cm in its profile contains chromas less than 2 and

redoximorphic features. If chromas between 40 and 50 cm were 2 or more, and no redoximorphic features with chromas of 2 or less were present within 100 cm of the surface, this soil would not qualify as hydric (Soil Survey Staff 1992). The annual high water table in the Mauvais soil occurs from April through October and ranges from 30 to 120 cm below the surface (Soil Survey Staff 1987).

Noonan North. The Fulda soil has an apparent water table at 30 to 90 cm below the surface from March through June annually (Soil Survey Staff 1987). Fulda is an Aquoll because its lower mollic epipedon has a chroma of 1 and its Bkg1 horizon has a 2.5Y hue, a chroma of 2 or less, and contains redox concentrations. If the lower mollic epipedon had not included 1 chroma color, the soil would have classified as a Vertic Haploboroll and would not have qualified as hydric (Soil Survey Staff 1992). Morphologic features indicative of wetness in the capillary fringe include redox features in the A horizon and the 13-cm-thick organic horizon overlying the mollic epipedon.

The Colvin-like soil has a seasonal high water table at the surface to 30 cm below the surface from April through July (Soil Survey Staff 1987). Chroma of 1 directly below the ochric epipedon makes this soil an Aquept. If the ochric epipedon were underlain by chromas of 3 or greater and redox features with chromas of 2 or less were not present within 75 cm of the mineral soil surface, this soil would not qualify as hydric (USDA Soil Conservation Service 1991). An organic surface horizon, redox features in the A horizon, and a pronounced calcic horizon are morphologic features found in the capillary fringe area. Both the Fulda and Colvin pedons exhibit dark, leached tongues extending 20 to 80 cm downward from the surface, although they were much more prevalent in the Fulda. Focused recharge in the microlows by ponded water probably formed the leached tongues, while net upward movement of water to the microhighs during drying periods concentrated solutes (calcium carbonate) between the tongues. The genesis of the Fulda and Colvin soils at this site appears to be similar to the genesis of Calciaquolls associated with recharge wetlands in the Red River Valley of North Dakota, as described by Knuteson et al. (1989).

The Heil soil has an apparent water table at 30 cm above to 30 cm below the surface from March through September (Soil Survey Staff 1987). Redox features and 1 chroma in the lower part of the mollic epipedon identify this soil as an Aquoll.

The Ranslo-like soil classifies as an Aquoll with its 1 chroma matrix and redox features in the lower mollic epipedon. The seasonal high water table occurs from April through June at depths of 30 to 90 cm below the soil surface (Soil Survey Staff 1987). Ranslo is not considered a hydric soil (USDA Soil Conservation Service 1991), although the taxadjunct described appears to have hydric characteristics. Redox features in the E and Btn horizons may be the result of capillary fringe saturation.

The Noonan series at the north end of the monitoring transect generally has a water table at greater than 180 cm below the surface, and has high matrix chromas in its lower B horizons, removing it from hydric soil consideration.

McLeod. The Venlo soil has a chroma of 1 and prominent redox concentrations in the lower mollic epipedon, thus easily meeting aquic criteria. The Hamar soil also has a chroma of 1 in the lower mollic epipedon, but lacks redox concentrations. Hamar is classified as an Aquoll because the color of the C1 horizon results from uncoated sand grains, and its landscape position is only slightly higher than the Venlo soil. Both soils support sedge meadow vegetation. The Ulen site has morphologic properties similar to the Hamar soil and is hydric for the same reasons. The major difference between the Ulen and Hamar sites is that Ulen supports true prairie rather than sedge meadow vegetation. The Hecla site also meets hydric soil criteria because the lower mollic epipedon has a chroma of 1 and contains common, prominent redox concentrations.

Indicators of the capillary fringe influence at the McLeod site include carbonate accumulations and redox concentrations in surface horizons of the Venlo and Hamar soils. The surface horizons of these soils are texturally finer than their lower horizons. These finer textures may allow capillary water to rise throughout the entire horizon thickness, depositing carbonates as the water evaporates and transpires. Redox concentrations in the A horizons of the Ulen and Hecla soils are believed to result from the presence of capillary water. The drying phase above 50 cm observed for the Hecla soil during 1991 supports this contention (Figure 7). Long-term data indicate a water table range of 0 to 75 cm below the soil surface for the Venlo and Hamar soils (Soil Survey Staff 1987). Data recorded at the McLeod site in 1991 are consistent with this range.

Preliminary Conclusions

Data collection to date on soil hydrology, anaerobiosis, and reduction at these sites is limited, and it is felt that no definitive conclusions about hydric soils can be made at this time. Monitoring instrumentation is being added at the sites and data collection continues. After a meaningful data set has been accumulated, being able to draw conclusions about the definition and recognition of hydric soils in the area is expected.

References

- Armstrong, C. A. (1967). "Geology and ground water resources of Divide County, North Dakota. County Groundwater Studies 6 - Part 3," North Dakota State Geological Survey, Grand Forks, ND.

- Armstrong, C. A. (1982). "Ground-water resources of Ransom and Sargent counties, North Dakota. County Groundwater Studies 31-Part 3," North Dakota State Water Commission, Bismarck, ND.
- Arndt, B. M. (1975). "Geology of Cavalier and Pembina counties," Bulletin 62, Part 1, North Dakota Geological Survey, Kaye's, Inc., Fargo, ND.
- Arndt, J. L., and Richardson, J. L. (1988). "Hydrology, salinity, and hydric soil development in a North Dakota prairie-pothole wetland system," *Wetlands* 8, 93-108.
- Aronow, S. (1982). "Lakes - coastal morphology." *The encyclopedia of beaches and coastal environments*. M. L. Schwartz, ed., Hutchinson Ross Publishing Co., Stroudsburg, PA, 509-513.
- Bluemle, J. P. (1991). *The face of North Dakota*. North Dakota Geological Survey, Bismarck, ND.
- Downey, J. S., and Paulson, Q. F. (1974). "Predictive modelling of effects of the planned Kindred Lake on ground-water levels and discharge, southeastern North Dakota," U.S. Geol. Sur. Water Res. Inv. 30-74, Bismarck, ND.
- Fenneman, N. M. (1931). *Physiography of western United States*. McGraw-Hill Book Co., Inc., New York.
- Hansen, D. E. (1967). "Geology and groundwater resources of Divide County, North Dakota. Part 1 - Geology," Bulletin 45, North Dakota Geological Survey, Grand Forks, ND.
- Harris, K. L. (1987). "Surface geology of the Sheyenne River map area," Atlas Series Map 15, North Dakota Geological Survey, Bismarck, ND.
- Knuteson, J. A., Richardson, J. L., Patterson, D. D., and Prunty, L. (1989). "Pedogenic carbonates in a Calciaquoll associated with a recharge wetland," *Soil Sci. Soc. Am. J.* 53, 495-499.
- National Oceanic and Atmospheric Administration. (1974). "Climate of the states, Volume II - Western states," U.S. Department of Commerce, Water Information Center, Inc., Port Washington, NY.
- Simmons, M., and Moos, D. K. (1990). "Soil Survey of Cavalier County, North Dakota," USDA Soil Conservation Service, U.S. Government Printing Office, Washington, DC.
- Sloan, C. E. (1972). "Ground-water hydrology of prairie potholes in North Dakota," U.S. Geological Survey Professional Paper 585-C, U.S. Government Printing Office, Washington, DC.

Soil Survey Staff. (1987). "North Dakota soil series interpretation records,"
USDA Soil Conservation Service, Bismarck, ND.

_____. (1992). *Keys to soil taxonomy*. SMSS Tech. Monograph
No. 19, 5th ed., Pocahontas Press, Inc., Blacksburg, VA.

Thompson, D. G., and Joos, L. L. (1975). "Soil survey of Richland County
and Sheyenne National Grassland area of Ransom County, North Dakota,"
U.S. Government Printing Office, Washington, DC.

Thornthwaite, C. W. (1948). "An approach toward a rational classification
of climate," *Geog. Rev.* 38, 55-94.

U.S. Department of Agriculture Soil Conservation Service. (1991). *Hydric
soils of the United States*. Miscellaneous Publication No. 1491, U.S. Gov-
ernment Printing Office, Washington, DC.

7 Preliminary Investigations of Hydric Soil Hydrology and Morphology in New Hampshire¹

Introduction

The University of New Hampshire and New Hampshire Natural Resources Conservation Service personnel are currently monitoring seven sites in New Hampshire, each consisting of a single pedon. The sites are in Hillsborough County, in the southern part of the State, which has a mesic temperature regime that borders on frigid. All of these soils are developed in sandy outwash materials and occur on level to very gently sloping outwash plains. Microtopography in this region consists of "pit and mound" features: convex swells and concave swales of relatively small area (usually tens of square meters or less), delineated by slopes of less than 1 percent. The pattern among these pits and mounds is often attributed to the positive geomorphic effect of tree root masses which form mounds following tree-throw and decomposition. Most of the "mound" soils best fit the Saugatuck series, and the "pit" soils are best represented by the Pipestone series. Landscape position and elevation relative to stream level suggest that these sites serve both recharge and discharge functions; it has been suspected that the ortstein in the Saugatuck soils contributes to some perching, or episaturation. Table 1 summarizes site locations, series, and taxonomy of the New Hampshire soils.

Materials and Methods

All measurements are taken biweekly. As of summer 1993, all but the Joppa Road and Francestown Turnpike sites were furnished with piezometers, platinum electrodes, and tensiometers. Sampling depths vary from site to site

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Table 1 Location, Series, and Taxonomy of Monitored Soils in New Hampshire			
Site Name	Coordinates	Series	Taxonomy
County Road	42° 51' 07" N 71° 35' 32" W	Pipestone	Sandy, mixed, mesic Entic Haplaquod/Typic Endoaquod
Francetown Turnpike	42° 56' 29" N 71° 44' 14" W	Saugatuck	Sandy, mixed, mesic, ortstein Aeris Haplaquod/Typic Endoaquod
Spring Road	42° 51' 36" N 71° 35' 43" W	Saugatuck and Pipestone	Sandy, mixed, mesic, ortstein Aeris Haplaquod/Typic Endoaquod; and Sandy, mixed, mesic Entic Haplaquod/Typic Endoaquod
Joppa Road	42° 53' 13" N 71° 30' 51" W	Saugatuck	Sandy, mixed, mesic, ortstein Aeris Haplaquod/Typic Endoaquod
South Hill Road	42° 56' 58" N 71° 42' 02" W	Pipestone-like	Sandy, mixed, mesic Entic Haplaquod/Typic Endoaquod
Swamp Road	42° 36' 37" N 71° 41' 52" W	Croghan	Sandy, mixed, mesic Aquic Haplorthod

because depths have been selected to correspond with genetic horizons, contrasting textures, and ortstein layers, as well as to the midpoint of the B horizon and approximately 25 cm into the C. At each sampling depth, duplicate piezometers and tensiometers and five platinum electrodes are installed. Table 2 summarizes monitoring device locations for each site. Water table levels are monitored by inserting a tape measure into the piezometers and recording water potential manually from tensiometer gauge readings. Redox potential is currently measured by connecting the platinum electrodes to a pH meter which has a zeroed potentiometer; initially (through 8/92), redox potential had been measured with a calomel pH electrode calibrated to pH 7. None of the sites have weather stations; therefore, precipitation and potential evapotranspiration data from the nearest weather stations will be used to assess the relationship of the climate during the study to 10- and 30-year averages.

Results

Soil saturation

County Road (Pipestone). Water table levels were between 20 and 30 cm approximately 35 percent of the time, primarily from January to April (Figure 1). The Bhsm horizon is the morphological marker of this flux point. The E horizon has never been saturated during this study; the Bhs has been saturated once in 5.5 years, even though faint mottling was detected in this horizon. The average water table depth is at about 40 cm, fluctuating frequently through the Bhsm and BC horizons, which have high chroma and redox concentrations. The C horizon is saturated almost constantly, except when the water table falls below 80 cm from August to October, but has no

Table 2

Location of Monitoring Devices (all tensiometers and piezometers are installed in pairs; five replicates of platinum electrodes are installed at each depth noted)

Site Name	Sensor Type	Depth, cm	Horizon
County Road	Piezometers	25, 53, 70	Bhsm, C1, C2
	Tensiometers	20, 25, 50, 76	Bhs, Bhsm C1, C2
	Pt electrodes	18, 25, 40	E, Bhs, BC
Francestown Turnpike	Piezometers	46, 80	2Cg1, 3C
	Tensiometers	35, 73	BC, 2Cg1
Spring Road Mound	Piezometers	22, 53	Bhs, C1
	Tensiometers	23, 53, 91	Bhs, C1, C2
	Pt electrodes	19, 29	E, Bsm
Spring Road Pit	Piezometers	33, 45, 63	Bhs, Bs, C
	Pt electrodes	20, 49	E, Bs
Joppa Road	Piezometers	25, 50	Bhs, C
South Hill Road	Piezometers	35, 55, 80	Cg1, Cg2, Cg3
	Tensiometers	35, 73	Cg1, Cg2
	Pt electrodes	11, 30	Ap, Cg1
Swamp Road	Piezometers	36, 68	Bs, C
	Tensiometers	30, 60, 90	Bsc, BC, C
	Pt electrodes	33, 50	Bsc, BC

redox depletions. Thus, saturation differences between the B and C horizons cannot be adequately discerned from morphology. Saturation patterns do not display any evidence of episaturation.

Francestown Turnpike (Saugatuck). Water table levels are above 40 cm briefly each spring, usually in April or May. The Bsc2 horizon is saturated less than 20 percent of the time, and the lower boundary of the Bsc1 marks that fluctuation point. The Bsc1 and A horizons have been saturated only once in 6 years, even though the Bsc1 horizon has apparent redox depletions. The 2Cg1 horizon, from 46 to 80 cm, marks the average (50 percent of the time) water table level; the water table drops below 1 m in August and rises to 80 cm by October. The 3C horizon, which is almost constantly saturated, has a matrix with chroma of 6 and redox depletions with chroma of 3. Again, morphological differences among soil horizons cannot be effectively correlated to saturation duration.

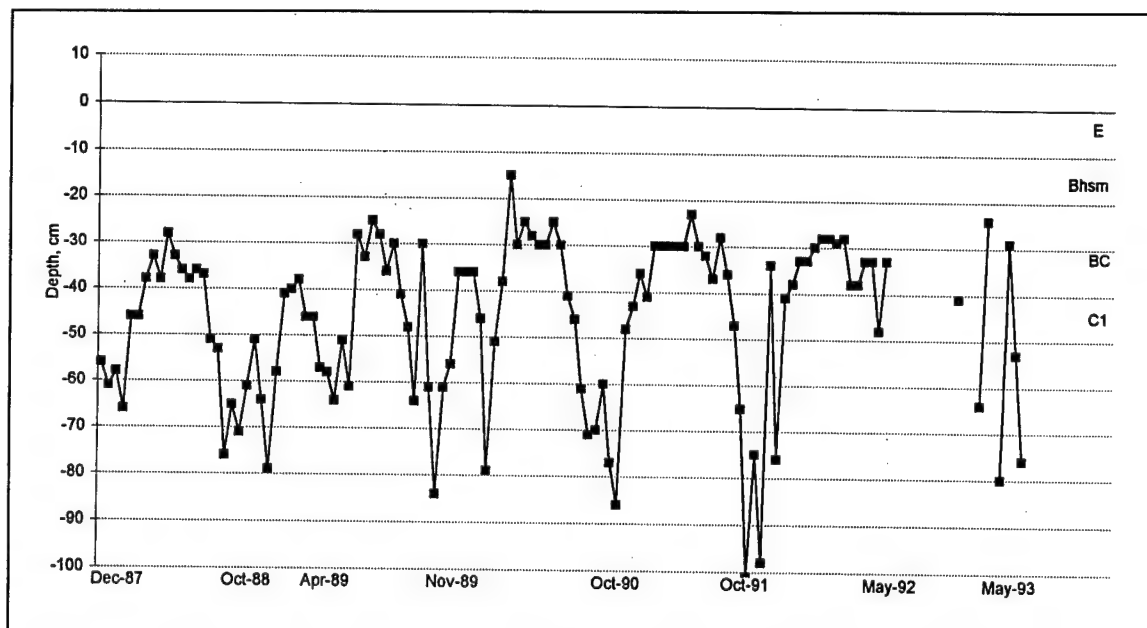


Figure 1. Water table levels, County Road (Pipestone series), December 1987 to June 1993

Spring Road mound (Saugatuck). Water table levels were at or above 20 cm about 20 percent of the time, saturating the Bhs and Bsm horizons through most of March and April and occasionally entering the lower E horizon. Water was also ponded briefly at this site in May of 1992 and April of 1993. Despite this, the E and Bhs horizons had no observable redox features, and the Bsm horizon has a chroma of 6, with redox concentrations. The primary fluctuation point of the water table (the 50-percent level) is marked by the Bsm horizon; the soil is saturated below 40 cm about 70 percent of the time, and redox depletions were observed in the BC horizon. There is no indication of episaturation; although water table levels have been monitored with wells in B and C horizons, water table levels have always been comparable in both sets of wells, and saturation of upper horizons is always concurrent with saturation in the lower profile.

Spring Road pit (Pipestone). Water table levels were at the surface approximately 60 percent of the time (Figure 2); the Oa and E horizons are saturated about 70 percent of the time, and this is reflected in the very thick (13-cm) O horizon and the variegated colors of the E. The water table falls below 40 cm (Bhs and Bs horizons) only during July and August, yet only the Bhs horizon, at 34 cm, contains redox depletions. Overall, evidence for endosaturation is strong.

Joppa Road (Saugatuck). Water table levels are above 20 cm from March to May, and at the surface briefly each spring. The E horizon is saturated for about 30 percent of the time, and the average water table level (50 percent of the time) fluxes through the Bhs and Bs horizons at 30 cm. There are no redox depletions in the saturated zone, although the E horizon is

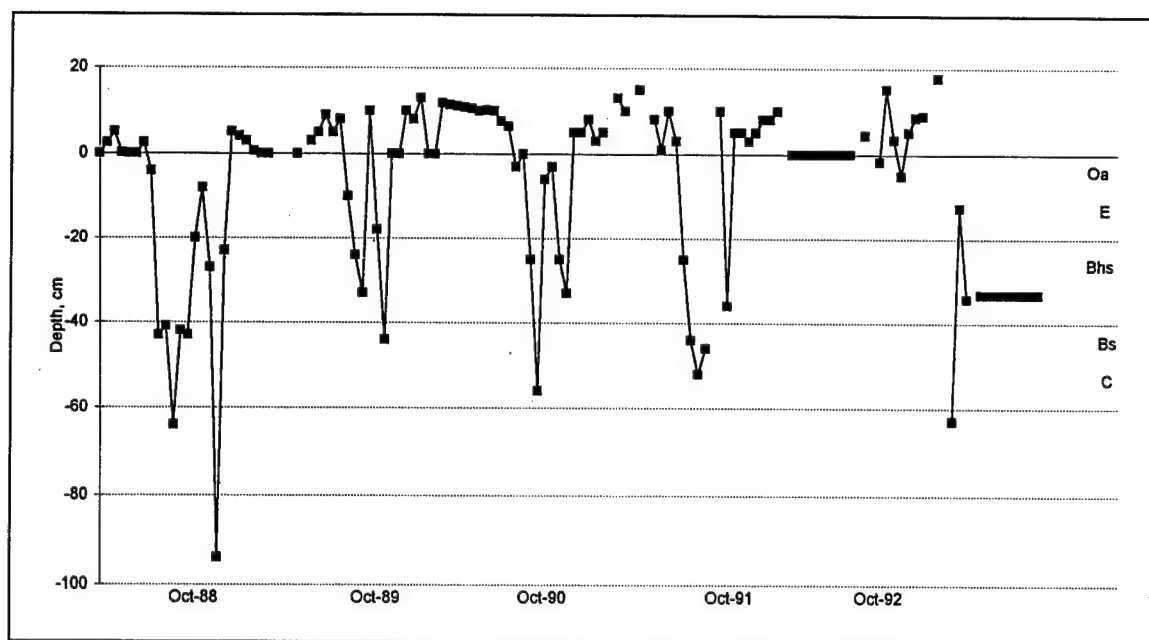


Figure 2. Water table levels, Spring Road pit (Pipestone series), March 1988 to November 1993

variegated and the Bs horizon contains redox concentrations. In most years, the water table drops to its minimum level of about 80 cm below the surface in the month of October. Endosaturated conditions appear to be the only type of saturation. Redox potential has not been monitored at the Joppa Road site because of problems with vandalism.

South Hill Road (Pipestone). The water table is at or within 5 cm of the surface, except during July and August, when it falls to 60 cm (Figure 3). There is no E horizon described in this profile, although the 10YR 4/1 sand grains are mixed into the A horizon, which is saturated most of the year. The C horizons are saturated 80-90 percent of the time, which is consistent with the reduced matrices of these horizons. A thin (5-cm) C horizon with chroma 6 at 74 cm may indicate subsurface lateral flow of oxygenated water along a textural boundary. Again, the primary mechanism seems to be endosaturation.

Swamp Road (Croghan). Water table levels here are rarely (three episodes between 1990-93) above 40 cm in the Bsc horizon, and saturation has never been recorded in the E horizon. The average water table level is between 40 and 60 cm, fluctuating through the Bs horizon; BC and C horizons are saturated 60-70 percent of the time, and both horizons contain redox concentrations. Despite the incipient ortstein, water table data indicate endosaturation at this site.

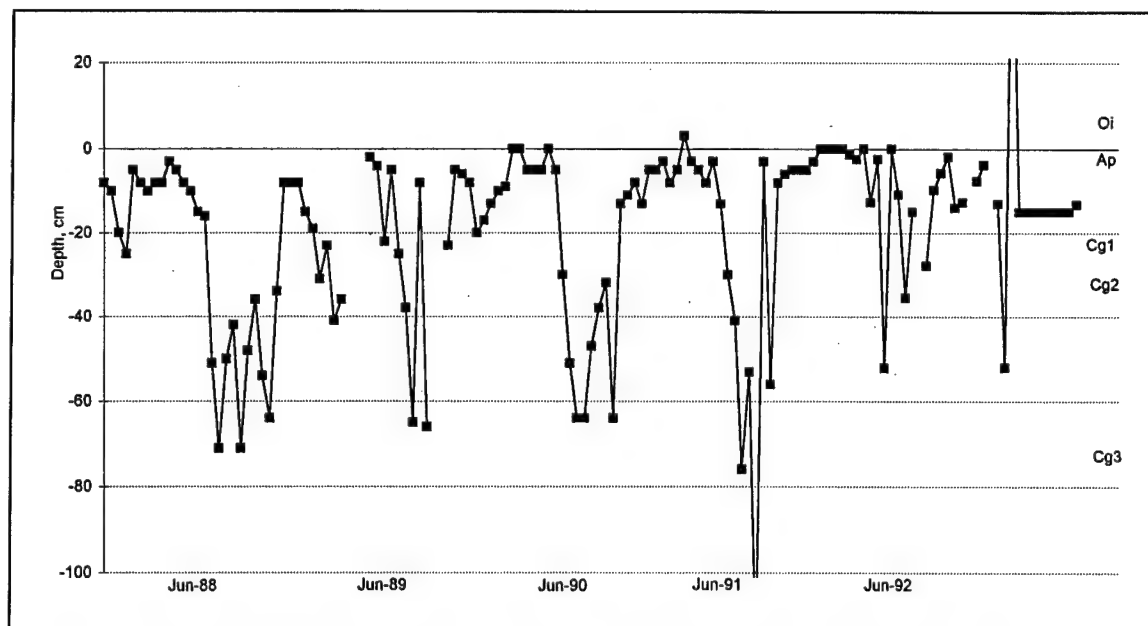


Figure 3. Water table levels, South Hill Road (Pipestone series), December 1987 to November 1993

Redox potential

County Road. Redox values for E, Bhs, and BC horizons are very similar (Figure 4), despite differences in saturation, although there is a slight trend of decreasing average redox potential with depth (Table 3).

Spring Road mound. Despite the difference in saturation levels (Figure 5), average redox values for the E and Bsm horizons are not significantly different (Table 3). They are substantially higher, however, than redox values for the Spring Road pit soil.

Spring Road pit. In this soil, redox potential is generally lower in the E horizon than in the Bs, despite differences in saturation duration which, although relatively small, would still tend to predict an opposite relationship.

South Hill Road. Average redox values of A and C horizons do not appear to be significantly different from each other (Table 3), although the A horizon values are higher than those of the nearly constantly saturated Cg1 horizon. Fluctuation patterns (Figure 6) are very different for the two horizons, however, particularly during the spring and early summer.

Swamp Road. Redox potential values are somewhat lower in the humus-rich Bsc than in the lower, and more frequently saturated, Bsc (Table 3), although fluctuation patterns in both horizons have approximately the same chronology.

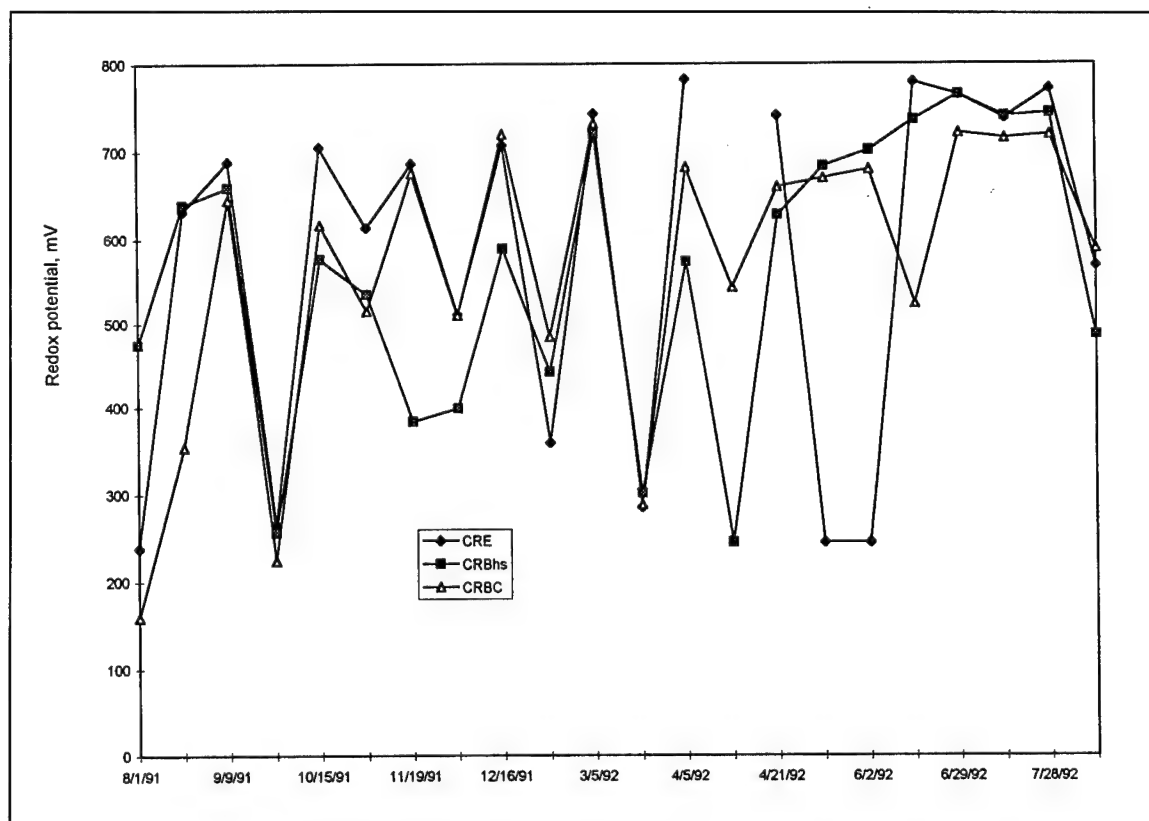


Figure 4. Redox potentials, County Road (Pipestone)

Table 3 Means and Standard Deviations for Redox Potentials, by Horizon					
Site	Series	Horizon and Depth	Mean, mV	Standard Deviation	Saturation Duration, %
County Road	Pipestone	E 8-13	575	209	0
		Bhs 13-20	565	170	0
		BC 31-48	558	164	50
Spring Road	Saugatuck	E 15-23	498	120	<5
		Bsm 25-33	480	149	50
	Pipestone	E 13-25	52	214	70
		Bs 34-49	77	168	85
South Hill Road	Pipestone	Ap 0-22	264	172	60
		Cg1 22-38	202	226	85
Swamp Road	Croghan	Bsc 26-33	524	226	<10
		BC 50-60	578	168	65

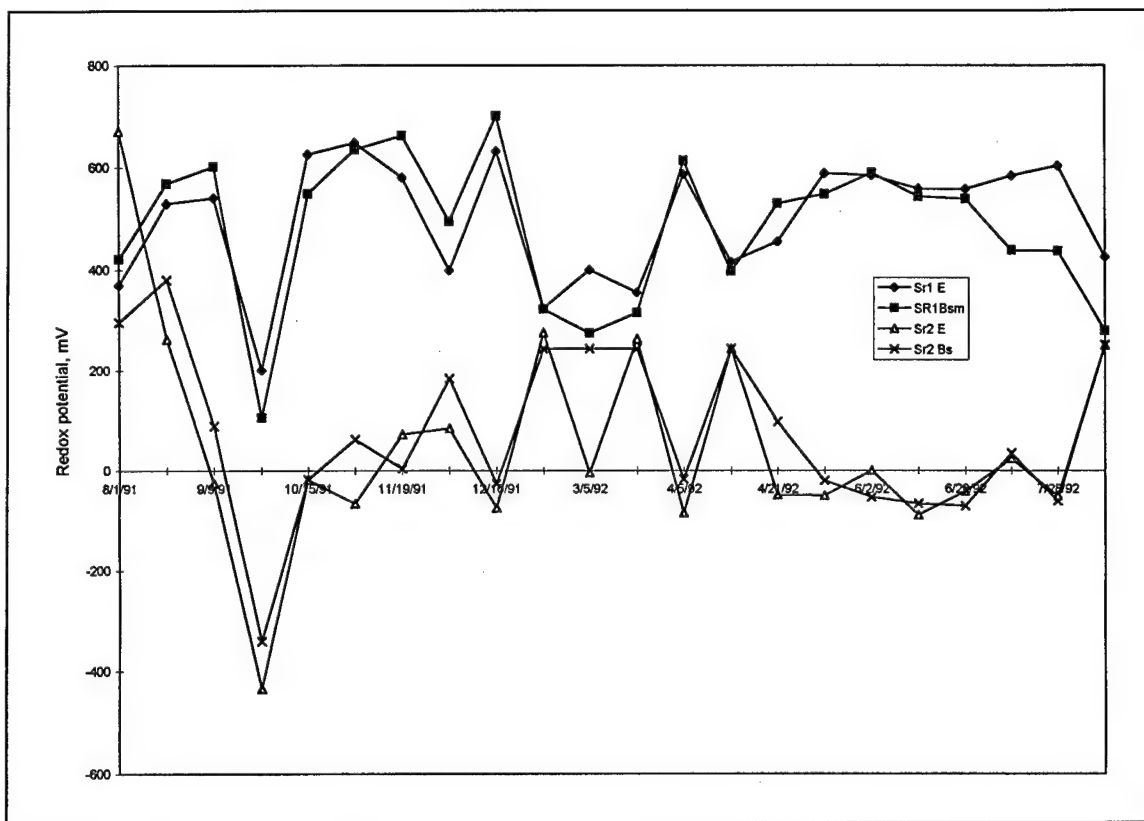


Figure 5. Redox potentials, Spring Road 1 (mound) and 2 (pit) (Saugatuck and Pipestone)

Discussion

In general, Pipestone soils were saturated at or near the soil surface considerably longer than Saugatuck and Croghan soils. The exception is the County Road Pipestone, which was saturated less frequently than the other Pipestone soils, and somewhat less frequently than most of the Saugatuck soils. The spodic horizons of the Croghan soil, as would be predicted from morphology and classification, were saturated less frequently than the Saugatuck spodic horizons. The Croghan BC horizon was, however, saturated slightly more frequently than the County Road Pipestone BC, although the Croghan BC is deeper (50 cm versus 31). Most of the soils in this study have the same seasonal timing for saturation, so that it would not be possible to confidently separate the relative effects of saturation duration and seasonality (or temperature effects) of saturation; soils that were saturated for the longest periods were also saturated for the longest periods during the period from April to October. Therefore, effects of seasonal water table fluctuation are probably most usefully described broadly, rather than looking for a particular temperature value correlation.

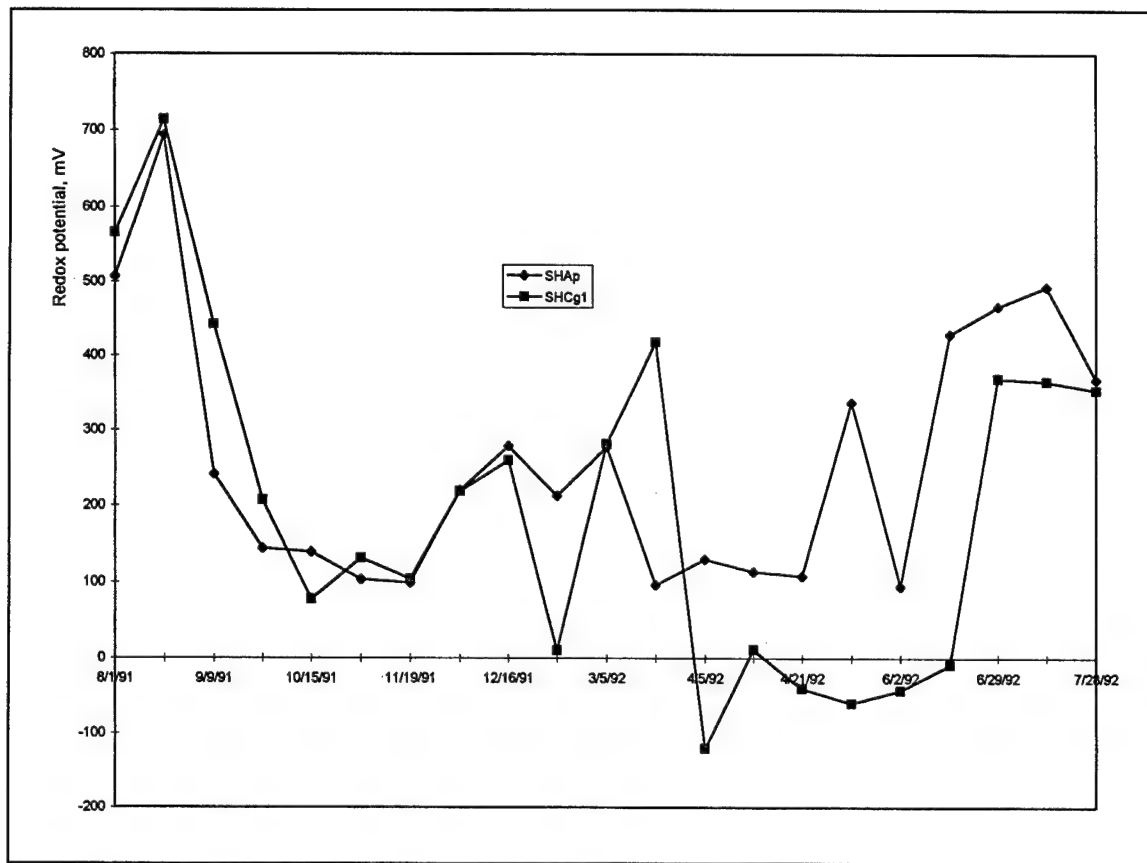


Figure 6. Redox potentials, South Hill Road (Pipestone)

On a horizon basis, soil color patterns did not correlate consistently with saturation duration. In some instances, such as the Swamp Road and County Road BC horizons, a similar saturation duration did correspond to similar color patterns. In other instances, though, there was virtually no correspondence: the Spring Road Pipestone Bs, the South Hill Pipestone Cg1, and the County Road Pipestone C2 were each saturated for about 85 percent of the time, yet the Bs had chroma 3 matrix with no redox features; the Cg1 had chroma 1 matrix with no redox concentrations or depletions; the C2 had chroma 6 matrix with redox concentrations. In some instances, as noted above, horizons with no recorded saturation had apparent redox features, while others were saturated without generating redox features. Two soils—the Joppa Road and Spring Road Pipestones—had variegated color patterns in E horizons which were saturated at least periodically. The other soils with E horizons—County Road, Spring Road Saugatuck, and Swamp Road—had no color variegation in the E, nor were those E horizons saturated during this period of observation.

The lowest mean redox value recorded was for the Spring Road Pipestone E horizon, which was saturated approximately 70 percent of the time and, as noted above, contained variegated colors. However, other horizons with similar saturation duration at the South Hill and Swamp Road sites had

considerably higher redox values. In addition, the Spring Road Pipestone Bs, which was saturated more frequently, had a slightly higher redox potential value than the E. Although a general relationship between saturation and reduction may enable reliable separation of Pipestone and Saugatuck soils in some cases, redox and saturation parameters for the County Road Pipestone soil were more similar to Saugatuck and Croghan values. Depths between otherwise comparable horizons were not necessarily consistent, however; the Croghan soil was considerably deeper than any of the others.

In summary, the two soils that were saturated most frequently to the soil surface had mean redox values that were substantially lower than those of soils which were saturated less frequently. In three of the soil profiles, redox potential decreased slightly with depth, although it increased slightly in the other two (Table 3). Since there was no evidence of episaturation in any profile studied here, the conclusion is made that the most frequently saturated horizons were closest to reduced values. Within most profiles, however, interhorizon differences in redox potential values were not substantial. Therefore, it is not possible to determine whether the differences in redox potential between horizons reflected oxyaquic conditions in lower horizons or capillary-fringe reducing conditions in upper horizons.

Another important consideration in interpreting redox potential is the extreme microscale variability, which may be a particular problem in coarser soils, such as those in this study. It may well be that the degree of variability precludes any usefulness of redox measurements in these soils. It is also well known that field measurements of redox potential are fraught with difficulties, even in homogeneous soils (if those exist!) because of difficulties assessing the extent and activity of other (than $\text{Fe}^{2+}/\text{Fe}^{3+}$) redox pairs and changes in pH and soil and dissolved gases. Thus, it seems more prudent to interpret in situ redox potential values by comparing differences of long-term means, rather than attempting to focus on a particular indicator value.

Effects of soil temperature

Saturation tends to be seasonal, with most pronounced effects during late fall, winter, and early spring, although most of these soils experience at least some saturation during the period from April to July. Redox potentials in most of these soils have not yet shown any pronounced seasonal trends. Most of these soils showed a sharp decrease in redox potentials around the middle of April, possibly coinciding with a temperature or microbial threshold. Lack of direct observation of soil solution species, soil temperature, and microbial activity (such as CO_2 evolution) requires that this observation remain in the category of pure speculation. At least, one does not feel comfortable asserting that there is a diagnostic relationship among these factors for the soils in this study. Further data may reveal such correlations, but they are not yet available.

Identifying hydric soils

Evaluation of hydric soils is based on the 1994 draft Field Indicators of Saturated Hydric Soils developed by the Natural Resources Conservation Service and currently undergoing field testing. The New Hampshire soils are in either mesic or frigid temperature regimes, and all of the soils in this study are sandy soils. Since categories MS and FS, and MA and FA, have nearly identical indicators, all soils in this study will be considered together.

Category M/FA (*For any soil: (1) Presence of hydrogen sulfide odor within 30 cm of the surface; (2) Hue is 5GY, 5G, or 5BG within 30 cm of the surface; or (3) Presence of muck in the mineral surface layer that is 5 cm or more thick*). At the Spring Road Pipestone site, saturation and reduction are sufficient that the hydrogen sulfide odor is detectable upon excavation. None of the soils in this study have the hues specified, nor are those hues common among sandy New Hampshire soils.

Category M/FO (*Classifies as a Histosol, except Folists*). All soils in this study are mineral soils.

Category M/FS2 (*For sandy soils: Presence of a layer of muck 3 cm or more thick (Mesic region), or 7 cm or more thick (Frigid region), value 3 or less and chroma 1 or less, on the mineral surface and under a root or leaf mat*). It is not clear whether "muck" can be used interchangeably with "sapric materials" in the hydric soil indicators. At the Spring Road Saugatuck and Pipestone and the Francetown Tpk Saugatuck, however, 3 or more cm of Oa is described, usually between an Oi and an E or A.

Category M/FS3 (*For sandy soils: Presence of albic horizon in which iron/manganese oxides have been stripped from the matrix exposing the primary base color of silt and sand grains with value 5 or more and chroma 2 or less. Translocated iron forms a diffuse splotchy pattern of two or more colors having value 5 or more and chroma 3 or 4 within 15 cm of the mineral surface*). Several soils in this study have albic horizons: County Road, Spring Road Saugatuck and Pipestone, Joppa Road, and Swamp Road. Of these soils, none has the requisite secondary colors with a value of 5 or more, and chroma of 3 or 4.

Category M/FS4 (*For sandy soils: Presence of ochric epipedon, 10 cm or more thick, or an umbric epipedon, having matrix value 3 or less and chroma 1 or less, determined on the individual silt and sand grains covered or masked with organic material. At least 70 percent of the visible grains must be covered to represent the matrix color*). The South Hill Road soil has an umbric epipedon; the rest are ochric with values of 3 or less. Of these, Swamp Road and Joppa Road have chroma of 1 or less, and are underlain by a horizon (E) with matrix chroma of 2 or less.

Category MS5 (*For sandy soils in Mesic regime: Presence in the upper 15 cm of matrix 60 percent or more depleted of iron with value of 5 or more*

and chroma 2 or less and distinct or prominent redox concentrations as iron masses). None of the soils in the New Hampshire study meet this criterion, despite the fact that nearly all of the soils in this study experience periodic saturation above 20 cm.

Preliminary Conclusions

Preliminary conclusions are as follows:

- a. Redox potential values must be interpreted with caution; probably, these data will be most useful in comparisons of long-term trends, rather than in development of a precise "reduced" value.
- b. A redox value that definitively indicates reduction cannot be derived from these data. Although the soils saturated most frequently had the lowest redox values, there was a great deal of difference in the mean values for these soils. Also, individual horizons with similar saturation duration did not have similar redox values. In the absence of iron speciation data and specific investigation of microbial activity, both as functions of temperature, it is impossible to be more specific.
- c. The plummeting redox potential described in Figures 4-6 occurs after a winter of saturation and at a time when saturated soils are likely to be warming. However, the specific values of those minima vary greatly among these soils. Furthermore, the redox recovery (increase) is also quite sudden and without a consistent relationship to change in saturation.
- d. As reduction cannot be definitively established from these data, and as interprofile differences in redox values are neither substantially different nor consistent in depth trends, it is not possible to determine whether the differences in redox potential between horizons can be interpreted as oxyaquic conditions in lower horizons or capillary-fringe reducing conditions in upper horizons. Also for these reasons, one cannot responsibly use these data to definitively correlate any specific morphological features to reduction at any depth.
- e. Most of the soils in this study could be assigned to the hydric soil category based on the presence of "muck," interpreted here as sapric materials, or an Oa horizon. The presence of an Oa horizon of appropriate thickness thus groups together soils which should reasonably be separated by other parameters.
- f. Many of the soils in this study—Spring Road mound and pit and Joppa Road—had variegated colors in the albic horizon that did not satisfy the draft list of hydric soil indicators because secondary colors often had chroma of 2 or less. All of these E horizons were saturated at least

periodically, suggesting that E horizon color variegation may be an appropriate indicator of saturation.

- g.* Classification into aquic suborders, particularly for Spodosols, requires recognition of redoximorphic features in an upper spodic horizon. Most spodic horizons in New Hampshire soils will not have chroma of 5 or more with a value of 2 or less, although they may have redoximorphic features. The draft list of hydric soil indicators would be easier to apply to the Aquods in this study if redoximorphic features in an upper horizon were recognized, with less emphasis on specific colors.
- h.* In sandy soils such as these, traditional estimates of seasonal high water table are often difficult to use. It is interesting, however, that determination of a major flux point, defined as the 50-percent frequency depth of the water table, often coincided with ortstein or incipient ortstein (Bsm, Bhsm, Bsc, or Bhsc horizons).

8 Preliminary Investigations of Hydric Soil Hydrology and Morphology in Oregon¹

Description of the Study Areas

Location, climate, and geomorphic setting

Two replicated transects were selected for study in the Willamette valley of western Oregon. One transect is in southern Benton County, near the north-east corner of Finley Wildlife Refuge, at latitude 44° 26' 00" N and longitude 123° 16' 18" W (Monroe 15' Quadrangle). The other is in southeastern Polk County, just west of Suver, at latitude 44° 44' 30" N and longitude 123° 12' 31" W (Albany 15' Quadrangle).

The climate of western Oregon is modified marine. Summers are warm and dry with some light rainfall. Winters are cool and wet, with occasional snow and some freezing temperatures. The mean annual precipitation at the OSU Corvallis Agri-Met weather station is 108.4 cm. The mean annual temperature is 11.2 °C.

The soils of western Oregon generally have mesic temperature regimes and xeric moisture regimes except, of course, for those wet soils that have aquatic moisture regimes. Most of the rainfall comes in the months of November through February, when farm fields are either fallow or cover crops are virtually dormant.

The Willamette Valley is a structural depression filled with Plio-Pleistocene and recent alluvial sediments (Baldwin 1981). Late Pleistocene flooding associated with the episodic formation and destruction of glacial lake Missoula left a sequence of three major stratigraphic units known collectively as the Willamette Formation (Balster and Parsons 1969). The oldest of these is known as the Irish Bend silts. These are overlain in places by the Malpass clay. The youngest flood deposit is the Greenback silt.

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The main floor of the Willamette valley consists of a series of terraces created by the Missoula floods and subsequent dissection by the Willamette River and its tributaries. Balster and Parsons (1968) identified these terraces and named them in terms of geomorphic surfaces. The two surfaces created directly by the Missoula floods are named the Calapooyia surface and the Senecal surface. The Calapooyia is a broad, flat surface of low relief and poorly formed drainage networks. Perched water tables are common, as water movement through the Malpass clay is very slow. The Senecal surface is more dissected and has primarily well-drained and moderately well-drained soils. The Malpass clay does not occur beneath this surface.

Alluvial surfaces created by post-Missoula rivers include the Winkle, Ingram, and Horseshoe. The Winkle represents the first floodplain formed; it has now been abandoned and occurs as a stream terrace. The Ingram represents the modern 100-year floodplain of the Willamette River system. Soils on it are more weakly developed than those on the Winkle. The Horseshoe surface is the current annual floodplain. It consists mainly of the gravel bars in and adjacent to the present channel.

Soils of the study area

Both transects were set up to sample a toposequence of soils representing a drainage catena on the Calapooyia geomorphic surface. The Benton County transect included the well-drained Willamette, moderately well-drained Woodburn, somewhat poorly drained Amity, and poorly drained Dayton soils on the Calapooyia surface and the poorly drained Waldo soil on the Ingram surface. The Polk county transect has only three sites on the Calapooyia surface representing the Woodburn, Amity, and Dayton soils, plus a Waldo site on the Ingram surface.

Irish Bend silts comprise the BCt and C horizons of all four soils on the Calapooyia surface. Only the Dayton soil contains the soil stratigraphic unit of Malpass clay, and the Bt horizons of Dayton have formed in this clay deposit. Surface horizons of all four soils have formed in the Greenback silts.

Both transects also included one site of poorly drained Waldo soil on the Ingram surface. Topographically, the Waldo sites occupy shallow swales that provide surface drainage for runoff from the Calapooyia surface. Waldo soils have formed in clayey alluvium that is a mixture of reworked sediments from erosion of the Calapooyia surface and sediments eroded from volcanic rocks higher in the Cascade mountains. Taxonomic, landform, and drainage class information for each soil at each site are given in Table 1.

Monitoring sites were selected by examining soils with an auger to determine that the soil at the site was representative of the series desired. Detailed profile descriptions and laboratory data were obtained later. Table 1 shows that pedons actually sampled did not fall exactly in the same taxa as the series for which each site was selected. The differences are minor, however, and

Table 1
Taxonomic, Landform, and Drainage Class Information for the
Soils of the Study Areas

Soil Name and Series Classification	Monitoring Site Pedon Classification	Landform	Drainage Class
Benton County			
Willamette (Wi-B) Pachic Ultic Argixeroll	Fine-silty, mixed, mesic Ultic Haploxeralf	Terrace	WD
Woodburn (Wo-B) Aquultic Argixeroll	Fine-silty, mixed, mesic Pachic Ultic Argixeroll	Terrace	MWD
Amity (Am-B) Argiaquic Xeric Argialboll	Fine-silty, mixed, mesic Aquultic Argixeroll	Terrace	SPD
Dayton (Da-B) Typic Albaqualf	Fine, montmorillonitic, mesic, Typic Epiaqualf	Terrace	PD
Waldo (Wa-B) Fluvaquentic Endoaquoll	Fine, montmorillonitic, mesic, Typic Epiaquoll	Swale	PD
Polk County			
Woodburn (Wo-P) Aquultic Argixeroll	Fine-silty, mixed, mesic Ultic Argixeroll	Terrace	MWD
Amity (Am-P) Argiaquic Xeric Argialboll	Fine-silty, mixed, mesic Typic Epiaqualf	Terrace	SPD
Dayton (Da-P) Typic Albaqualf	Fine, montmorillonitic, mesic, Typic Epiaqualf	Terrace	PD
Waldo (Wa-P) Fluvaquentic Endoaquoll	Fine, montmorillonitic, mesic, Typic Argiaquoll	Swale	PD

these authors feel that the sites selected are good sites with respect to differences in hydrology and the development of redoximorphic features important in defining hydric soils.

The Wi-B pedon, for example, was classified as an Alfisol only because the base saturation of the second horizon was less than 50 percent, an artifact that is entirely due to agricultural management. The Wa-P soil appeared to have some clay films, so it was classified as an Argiaquoll instead of an Endoaquoll.

Sources of water and hydrodynamics

Depth and duration of saturation are controlled by the input and outflow of water. Most inputs to all sites were from precipitation, which occurs almost entirely as rain. The Calapooyia geomorphic surface is a broad, flat surface that receives very little water input from higher landscapes. The Benton County transect, however, was located close enough to an isolated butte that

some sites may have received some water as runoff from the higher slopes, or as throughflow discharging into the soils of the transect. In both transects, the Waldo soil on the Ingram surface received some water as runoff from the adjacent Calapooyia terrace and some water from surrounding areas higher in the drainage basin of the swale.

Internal water flow in these landscapes is controlled in part by the very slowly permeable Malpass clay. Where this soil stratigraphic unit is present, vertical flow is greatly restricted, and water tables build up above this layer, often saturating the soil to the surface. This creates a reducing environment that results in iron depletion and development of an E horizon in the Dayton soils. Water flows laterally, both within the soil and over the soil surface, ultimately discharging into the swales of the lower Ingram surface. Where the Malpass clay is absent, water movement through the soil is more uniform, and water tables rise and fall in the soil in concert with the timing and amount of precipitation input.

Methods

Instrumentation

Piezometers were used to record water table depths because of the known stratigraphic differences in these soil landscapes. No open bore holes or unlined wells were installed. Tensiometers were used to measure soil moisture status in unsaturated soil. Mercury junction platinum electrodes constructed according to the method of Faulkner, Patrick, and Gambrell (1989) were used to measure redox potentials. A calomel electrode was used for reference, and all readings were corrected to standard electrode potentials by adding 244 mV. Chromel-Alumel thermocouples were used to record soil temperatures.

Piezometers, tensiometers, and platinum electrodes were all installed in triplicate at each of three depths: 25, 50, and 100 cm. In some soils, these depths were modified slightly to correspond with observed soil horization. Particularly in those soils that contained restrictive clay layers, these authors wanted to be sure that one set of readings was in soil above the layer, one set was within the layer, and one set was below it. In other soils, minor adjustments were made only to ensure that instruments were placed within a horizon, rather than at the boundary between two horizons.

Single thermocouples were placed at the same depths as the piezometers and electrodes. There was no replication at a given depth at a given site. A single piezometer was installed at a depth of 200 cm to track the water table as it rose from below.

Monitoring schedule

Measurements were made every week from October through the first week of June for both the 1991-1992 and the 1992-1993 rainy seasons. Measurements were made only once a month from June through September in both years. Groundwater tables, redox potentials, matric potentials, and soil temperatures were recorded every time sites were visited to make measurements.

Precipitation in relation to "normal"

According to the weather summary dated June 1992, published by the Oregon Climate Service at Oregon State University, precipitation was 69 percent of normal between 1 October 1991 and 30 June 1992. This period, which includes the first year of wet soils monitoring, was considerably warmer and drier than normal.

The second year, from 1 October 1992 through 30 June 1993, was almost exactly the opposite. The spring months were cooler and wetter than normal, followed by early summer conditions that were the coolest and wettest on record. Precipitation was above normal for 5 consecutive months from February through July. The fall of 1993 was then warm and dry. Despite the wetter than normal conditions in midyear, the 1992-1993 water year (1 October - 30 September) was still the seventh consecutive drier than normal year, but only by about a centimeter of rainfall.

Figure 1 shows the relationship between precipitation and water table observations at the Dayton site in Benton County for these 2 water years. Precipitation for the 1991-1992 rainy season occurred each week from November through the first week of May. During this period, each month except March had at least one weekly accumulation of > 1 cm of rainfall. For the 1992-1993 rainy season, each month from November through June had a weekly accumulation of rainfall exceeding 1 cm. Precipitation data for the Polk County sites were not identical to those shown in Figure 1, but the shape of the distribution was very similar.

Results and Discussion

Soil saturation and reduction

Figure 2 shows selected water table depths in relation to landscape position and soil horization for the soils of the Benton County transect. After the onset of the rainy season in November (Figure 1), water tables rose in all soils of the transect. By January, water tables in the poorly drained Dayton soil and the somewhat poorly drained Amity soil were at or near the surface both years. The early spring months in 1992 were very dry, so that by April, water tables in all but the well-drained Willamette soil were lower than they were in January. In 1993, however, the spring months were very wet, and

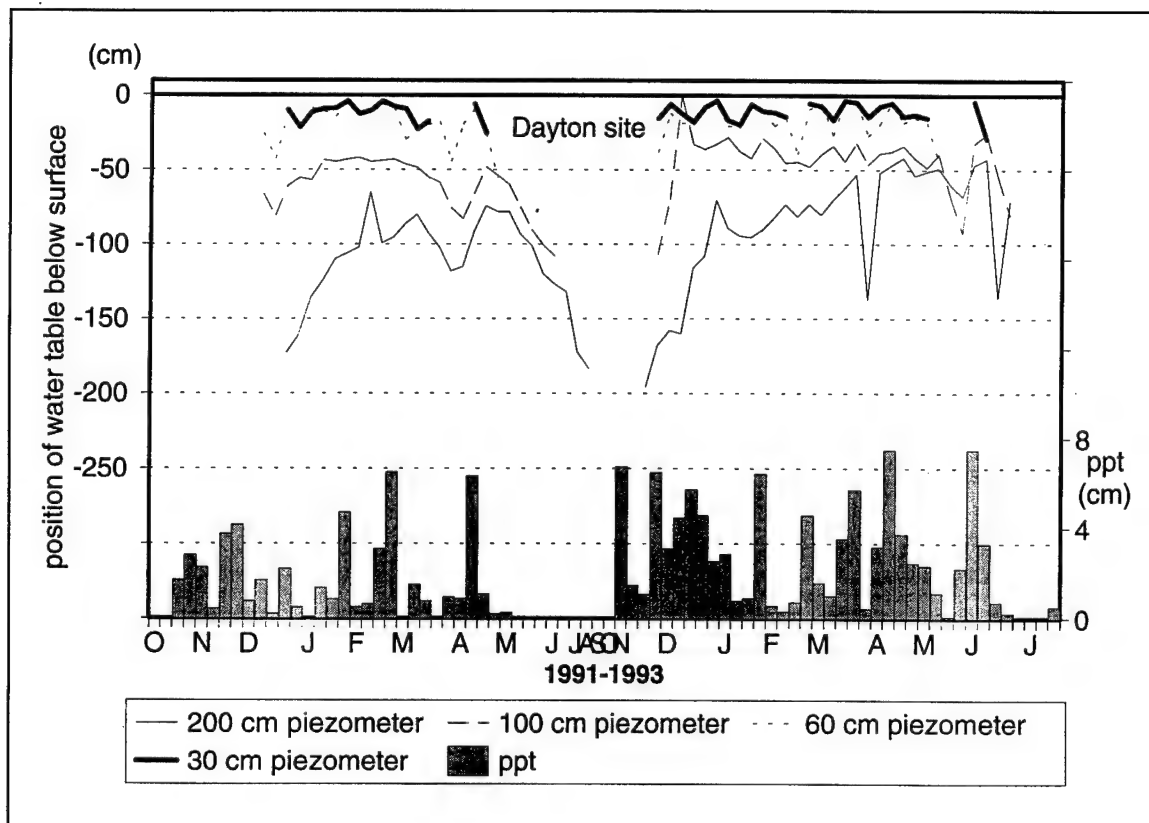


Figure 1. Precipitation (bottom) and water table data for Dayton site in Benton County

April water tables were at or above the levels observed in January. This was also true for the well-drained Willamette soil, although the depths to the water table were generally greater in this soil than in the more poorly drained landscape associates. However, the April water table depth in the moderately well-drained Woodburn soil was not above the January water table depth. The Woodburn soil location is near a terrace escarpment that probably facilitated drainage of the study site and is manifest as the lower April water table.

Relationships between saturation, anaerobiosis, and reduction. Figure 3 illustrates the relationships between duration of saturation and soil redox potentials as measured with platinum electrodes for one site, the Dayton soil in Benton County. In this figure, the heavy black line at 200 mV indicates the redox potential at which iron is reduced from the ferric to the ferrous state. Similar graphs were made for each monitored site in both transects, and the data from all of those graphs are summarized in the following paragraphs.

The point at which redox potentials fall below 350 mV is taken as the onset of anaerobiosis. At this point, the soil is not completely anaerobic, but oxygen availability is low enough, particularly in some microsites, that nitrate and manganese are probably serving as alternate electron acceptors.

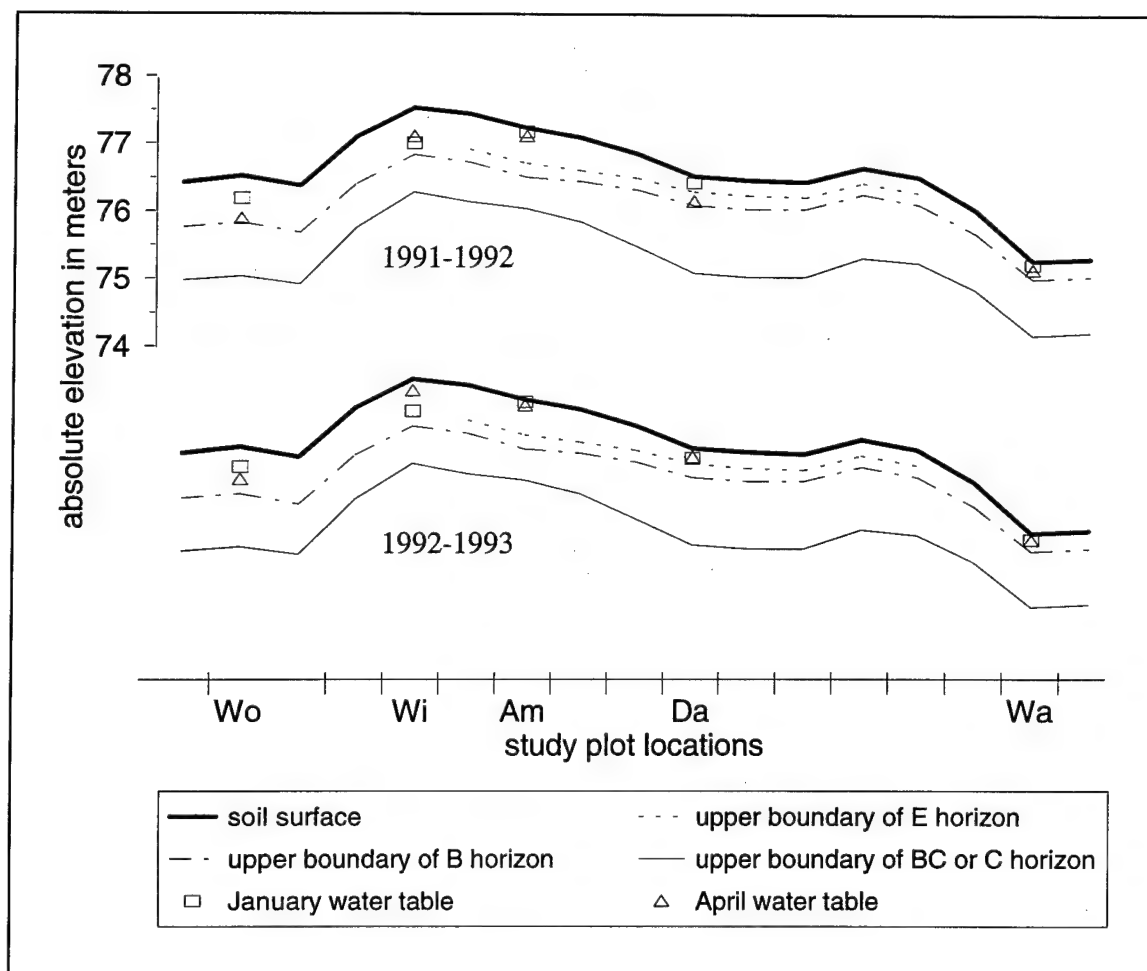


Figure 2. Benton County transect water table depths

The point at which redox potentials fall below 200 mV is taken as the onset of reduction. At this point the soil probably is completely anaerobic, and it is likely that nitrate is no longer available as an electron acceptor. Thus ferric iron is the principal electron acceptor, and as long as redox potentials remain low and there is a supply of ferric iron, iron will be continually reduced.

No evidence of sulfate reduction was seen in any of the soils studied, and there is no threshold for such intense reduction postulated for these soils.

Figure 3 illustrates a general trend for redox potentials at all depths to be well into the oxidizing range at the end of the warm, dry summer. With the onset of saturation after the beginning of the rainy season, redox potentials decline. For the Dayton soil data shown in Figures 1 and 3, there is a lag of about 2 months between the onset of precipitation in the fall and the onset of saturated conditions in the soil. Then there is an additional lag of about 1 month before redox potentials decline to the point of onset of anaerobiosis. The soil does not become reducing until it has been saturated continuously for

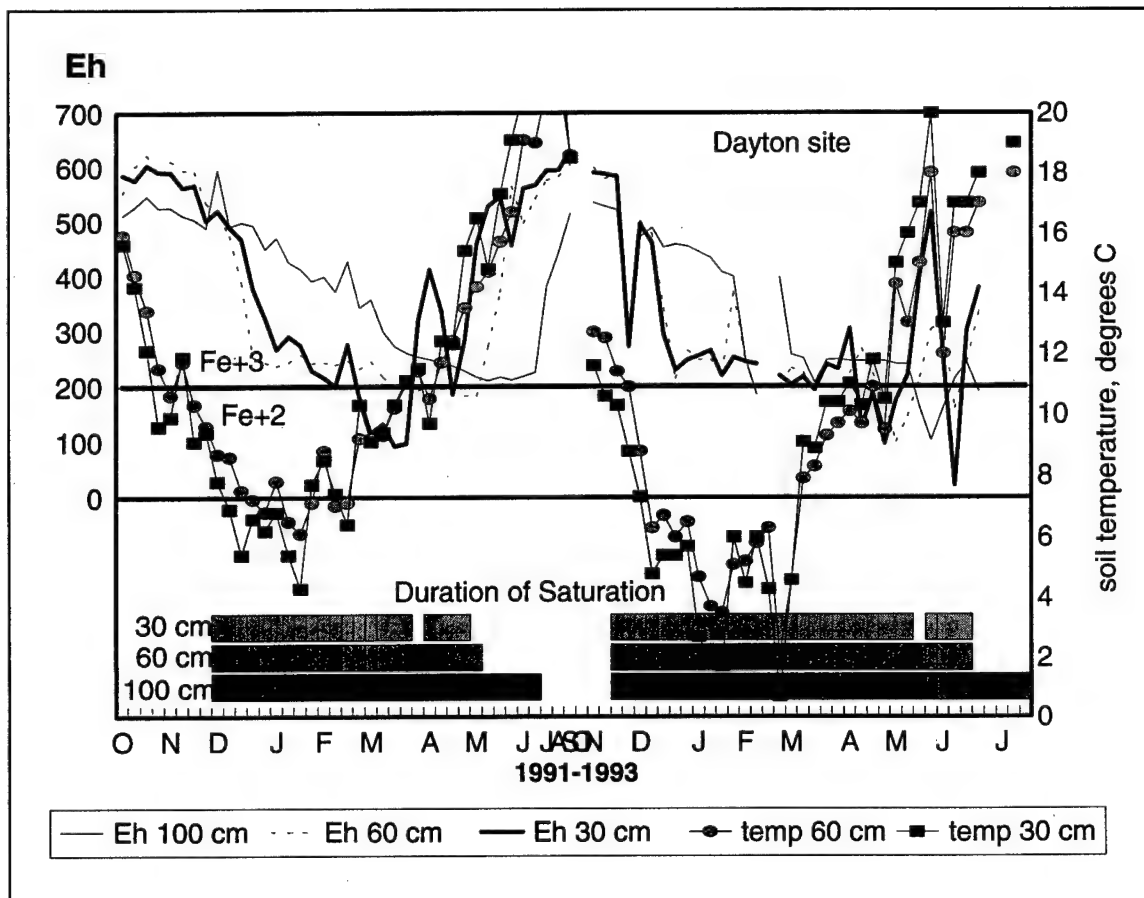


Figure 3. Duration of saturation and redox potential for Dayton site in Benton County

3 to 4 months. These same trends were observed in all of the other soils, with variations occurring both as a function of soil drainage class and seasonal rainfall.

Figure 3 also illustrates a general trend for redox potentials near the soil surface to respond more quickly to changes in both saturated conditions and soil temperatures than redox potentials deeper in the soil. This is undoubtedly due to higher amounts of organic matter and higher populations of soil microorganisms in surface soils, hence more electron production and more redox activity. This trend, too, varies significantly with soil and landscape differences and variations in rainfall from year to year.

In the well-drained and moderately well-drained soils, redox potentials at 25 and 50 cm rarely dropped into the zone of anaerobiosis during the 1991-1992 rainfall year. Saturation at these depths was also rare, and the duration of saturation events was never more than a week at 25 cm, nor more than 4 weeks at 50 cm. Similar trends were observed in the 1992-1993 rainfall year, except that with much more spring rainfall, there were a few more events of short-term saturation and anaerobiosis. These soils were not

expected to be hydric soils, and the data support the interpretation that they are not hydric.

The two somewhat poorly drained soils both had much more prolonged periods of saturation and lower redox potentials, but they did not replicate each other very well. The Amity soil in Polk County (Am-P) became anaerobic at 35 cm after about 3 months of saturation in 1991-1992, and after about 4 months of continuous saturation in 1992-1993. Redox potentials never fell into the reducing zone (<200 mV) at any depth at any time during either rainy season.

In the Benton County Amity soil (Am-B), the lag time between saturation and anaerobiosis at both 25 and 50 cm was only a month in both years. The soil remained saturated for a longer time than the Polk County soil, and redox potentials were generally lower. In 1991-1992 the redox potential at 25 cm dropped into the reducing zone briefly after 3 months of saturation. In 1992-1993, the soil became reducing at both 25 and 50 cm in the spring, after 5 months of continuous saturation. At this time, soil temperatures were rising, and lower redox potentials were attributed in part to increased biological activity.

The Amity series is somewhat poorly drained and is not a hydric soil according to the current database criteria. The reason is that the water table information on record in the database indicates that the water table is deeper than 6 in. Field data, however, show that the water table in the Polk County site does fluctuate above 6 in. for brief periods throughout the rainy season, and in the Benton County site, the water table persists above 6 in. most of the time from December to April.

Both poorly drained Dayton soils had distinctly perched water tables, the Malpass clay serving as a very effective aquiclude. These soils were saturated at both the 35- and 60-cm depths in Polk County (Da-P) and 30- and 60-cm depths in Benton County (Da-B) virtually continuously from December to May. During the exceptionally wet spring of 1993, saturation lasted well into June. The lag time between onset of saturation and onset of anaerobiosis was about 3 months at the Polk County site and about 1 month at the Benton County site. This was true for both sampling depths and for both rainy seasons. The Benton County data (Figure 3) show a marked decline in redox potentials in late November of 1992, but these are believed to be anomalous readings that do not reflect the true nature of the soil environment. The fact that readings at all three depths were nearly the same and are way out of line with respect to trends observed in other soils and other years leads one to suspect instrument error as the source of these peculiar readings. As a result, these data were not used to determine the lag time before anaerobiosis in this soil.

Redox potentials in the Polk County Dayton soil never fell below the 200-mV threshold for reduction, although the potentials at both 35 and 60 cm fell to almost that level in March and April, particularly in the very wet

second year of the study. Redox potentials at 100 cm remained near 400 mV throughout both years, despite the fact that the soil was continuously saturated at this depth from December through June. Lack of organic matter and organisms is the most likely explanation for this absence of reduction in a saturated environment.

The Benton County Dayton soil appears to be a much wetter soil, based on height and duration of the water tables, the onset of anaerobiosis and reduction, and the redox potentials. During the first year, the soil at 30 cm became reducing after about 3 months of saturation, and the soil at 60 cm became reducing after about 5 months of saturation (Figure 3). The soil at 100 cm never quite became reducing, but the redox potentials did drop to nearly 200 mV and remained there for several months. During the second year, the lag times preceding reduction were 5 months at 30 cm and 5 1/2 months at 60 cm, and the reduction at these levels corresponded nicely with the combination of heavy spring rainfall and rising soil temperatures. Redox potentials at 100 cm followed the same trend in the second year as the first, with one episode of reduction occurring late in the spring.

The Dayton series is classified as a hydric soil, and the data from this study support that conclusion.

Both poorly drained Waldo soils were saturated within 50 cm of the soil surface continuously from December to May the first year and from December to June the second year. Piezometric heads were essentially the same in all piezometers, suggesting the presence of an apparent, rather than a perched water table, although there were a few episodes of surface ponding while the water table in the soil remained below the surface.

The lag time preceding anaerobiosis at the Polk County site (Wa-P) was 2 weeks the first year and 4 months the second year at the 35-cm depth. At 65 cm, the lag times were 4 weeks the first year and 4 months the second. At the Benton County site (Wa-B), the lag times at 25 cm were 1 month the first year and 6 weeks the second. At 50 cm, the lag times were 2 months the first year and 1 month the second year.

Despite long periods of saturation, neither site exhibited much reduction. During the first year, both sites had one brief period when redox potentials at 35 cm (Wa-P) and 25 cm (Wa-B) fell just below the 200-mV threshold 3 months after the onset of saturation. Reducing conditions did not occur at greater depths in either soil. During the second year, reducing conditions did not occur at all at the shallow and intermediate depths, and only in the Benton County site did reducing conditions occur a few short times at 100 cm after 4 months of continuous saturation.

Thickness of reduced zone above a water table. Water tables in the Amity, Dayton, and Waldo soils generally hovered at or near the surface for several months during the winter rainy season. It is not possible to identify a reduced but unsaturated zone above a water table when the water table

periodically reaches the soil surface. It is true, however, that the strongest reducing conditions were observed in these soils at the 25- to 35- and 50- to 65-cm depths.

Water tables in the Woodburn and Willamette soils did not reach the surface but fluctuated markedly in response to rainfall events. Reducing conditions, as indicated by redox potentials less than 200 mV, were rarely observed in the soil at the depths at which water table fluctuations occurred. Morphological evidence of reduction in the form of low chroma colors and a few fine concretions is present at depths ranging from 41 cm in the Woodburn soils to 69 cm in the Willamette soil.

Evidence of oxyaquic conditions. The poorly drained Waldo soils had continuous saturation for several months, yet rarely did redox potentials fall below the 200-mV threshold for iron reduction. These soils occupy a landscape position that collects and transmits water as stream flow. It is possible, therefore, that the groundwater in these soils is a little more oxygenated than water beneath the Calapooyia surface, hence the lack of reducing conditions. These soils do have redoximorphic features in the form of 1 chroma matrix colors, soft iron masses, and concretions. Hence, they do not meet the concept of oxyaquic conditions. These authors do not have data on α, α' -dipyridyl reaction to determine whether or not reduced iron is present.

Effects of soil temperature

Timing of anaerobiosis and reduction in relation to soil temperature. The data shown in Figure 3 illustrate the kinds of relationships observed in all of the study sites. Soil temperatures decline more or less steadily from the beginning of field measurements in October until January or February, when they begin to rise again. The winter of 1992-1993 was colder than the one before, and the warming trend was about a month later.

Soil temperature is, at best, very weakly related to the onset of anaerobiosis in the soil. Anaerobiosis is much more directly related to the onset of saturation, regardless of soil temperature. In 1991-1992, anaerobiosis in the surface soil began in late December, about a week after the onset of saturation, when the soil temperature was a little over 6 °C. The next year, anaerobiosis also began in late December, but it was about a month after the onset of saturation, and the soil temperature was about 5 °C.

Reduction does appear to be more closely related to soil temperature. In general, reducing conditions were not observed until 3 to 5 months after the onset of continuously saturated conditions. At this time, soil temperatures had begun to rise, such that biological activity increased, yet the soil was still anaerobic, so iron was more readily reduced. A detailed analysis of this relationship has not been done, but cursory examination of the data indicates that the temperature threshold at which this occurs is at 8 to 10 °C.

The temperature threshold at 5 °C is essentially irrelevant for these soils. Almost all soil temperatures lower than 5 °C were observed at the 25- to 35-cm depth, and in almost all cases the duration of temperatures this cold was very short. There is no apparent correlation between redox potentials and temperatures colder than 5 °C even when the soil was that cold for 3 consecutive weeks.

Growing season relationships. In modified marine climate, plants grow actively during the spring, summer, and fall months, but the season of maximum rainfall and soil wetness is the winter. The growing season defined by the mesic temperature regime is 1 March through 31 October, yet the months of November, December, January, and February are the wettest of the year. Thus the mesic/xeric combination creates the possibility that one could have soils that were very wet for 3 or 4 months during the winter, then dried out sufficiently before the defined beginning of the growing season to fail hydric soils criteria. This did not happen in any of the wet soils observed over 2 years, but only because saturated conditions and reducing soil environments persisted well into March, and in the second year, through May, such that the growing season criteria for hydric soils were met.

The actual growing season for soil microorganisms cannot be predicted from either the mesic temperature regime or the 28 °F (-2 °C) or 32 °F (0 °C) air temperature thresholds. The reason is that microbes are active throughout the year, even in the nongrowing season winter months. The evidence for this is that redox potentials fall markedly after the soil becomes saturated, and even though the soil does not become fully reduced until later in the spring, it is definitely anaerobic, indicating that organic matter is being decomposed with the production of electrons in need of electron acceptors.

On the other hand, both the beginning of the mesic growing season and the beginning of the 28 °F growing season correspond reasonably well with the time at which soil temperatures have risen to the 8-10 °C range, which gives rise to a flush of microbial activity that results in rapid decline of redox potentials and the onset of reduction of iron. The 32 °F growing season does not begin until late April or early May, well after the marked change in biological activity and redox potentials that takes place when the soil temperatures have risen to the 8-10 °C range. None of the ending dates for the growing season as defined by any method bear any relationship to microbial activity, as redox potentials remain high until the soil has been saturated by late fall rains for about a month.

Identifying hydric soils

Morphological features for differentiating hydric from nonhydric soils. The well-drained Willamette soil (Wi-B) and the two moderately well-drained Woodburn soils (Wo-B, Wo-P) are not hydric soils. The well-drained soil has no redoximorphic features above 69 cm. There are some concretions in the soil between 69 and 124 cm and soft iron masses below 124 cm. The

moderately well-drained soils have no redox depletions in the upper 41 cm. One soil had common fine faint soft iron masses between 26 and 41 cm; the other had no redox concentrations in the upper 41 cm. Both soils had low chroma redox depletions, high chroma soft iron masses, and hard black iron-manganese concretions in the soil below 41 cm. Redox potentials never fell below the 200-mV threshold for reduction in the Woodburn soils, and did so only once in the Willamette soil, in the late spring of the very wet 1992-1993 observation year.

The poorly drained Dayton and Waldo soils are hydric soils. The Dayton soils have prominent E horizons at shallow depth above a very slowly permeable claypan. High chroma iron masses occur both in these horizons and in the surface soils above them. Iron-manganese concretions are present in the E horizons of the Dayton soil and are also found in the surface horizons of one of the Dayton soils. The Bt horizons of the Dayton soils have low chroma matrices with both high chroma iron masses and Fe-Mn concretions. One Dayton soil (Da-B) had redox potentials less than 200 mV both years, but the other (Da-P), though becoming quite anaerobic both years, never developed potentials less than 200 mV.

Waldo soils are distinguished by the presence of 1-chroma matrices at depths between 25 and 75 cm. These horizons also contain at least a few high chroma soft iron masses. One of the soils also has Fe-Mn concretions throughout, but the other does not. Both soils have high-chroma soft iron masses in the surface horizon. Redox potentials in both soils dropped into the reducing zone during 1991-1992, but only one soil (Wa-B) exhibited reducing redox potentials in 1992-1993.

The somewhat poorly drained Amity soils are not hydric according to current criteria. The only reason for this is that the water table depth is given in the database as 15-46 cm (0.5-1.5 ft), which does not qualify as less than 15 cm. Water table data for 1991-1992 would support this interpretation, as the water table was generally below 15 cm by the start of the mesic growing season, even though the soil at 25 cm was saturated almost continuously from December through February. In 1992-1993, however, excessively wet conditions caused water tables to remain within 15 cm of the surface well into the growing season, thereby meeting hydric soils criteria for this year.

Morphologically, the Amity soils are very similar to the Dayton soils, except there is no abrupt textural change between the E horizon and the Bt horizon. The A and E horizons contain high chroma soft iron masses throughout, however, and the E horizons contain Fe-Mn concretions. Redox potentials in the Amity soils also exhibited trends similar to those identified in the Dayton soils.

In summary, the morphological features that distinguish the hydric soils from the nonhydric soils are matrix colors and presence of redoximorphic features. Nonhydric soils have high chromas to depths of at least 41 cm; redox depletions do not occur in the upper 41 cm; and there are no redox

concentrations in the upper 26 cm. Hydric soils have dominantly 1 and 2 chroma matrix colors in all horizons and have redox concentrations of soft iron masses in all horizons from the surface down. Many also have concretions of iron and manganese.

Morphological features in the capillary fringe. Because water tables fluctuate up and down, both during a single season in response to rainfall events, and from season to season depending on total rainfall, one cannot identify a capillary fringe that is consistently wet but never saturated. The somewhat poorly drained and poorly drained soils had water tables right at the soil surface at least some of the time during the rainy season, especially in the very wet spring of the second year.

The moderately well-drained and well-drained soils showed some evidence of periodic but very short-term water tables at depths above those at which redoximorphic features were observed. Thus, rather than a capillary fringe effect, evidence of occasional saturation without reduction is seen in these soils.

Preliminary Conclusions

The growing season criterion is not particularly useful for soils in the modified marine climate of the Pacific northwest. Redox potential data indicate that microbial activity continues all year, even when the soils are saturated and cold during the winter months.

Soil temperature of 5 °C does not correlate with microbial activity, anaerobiosis, or reduction. However, a temperature of about 8 °C on the rising arm of the annual soil temperature curve does seem to be a threshold for a flush of renewed microbial activity, which when coupled with soils that are still saturated after 4 or 5 months, causes a marked decline of redox potentials to the point that iron can be reduced. There does appear to be some correlation between the time at which the soil temperature reaches 8 °C and the beginning of the growing season as defined either by the mesic temperature regime or by the -2 °C (28 °F) growing season. The 0 °C (32 °F) growing season does not correlate with soil anaerobiosis or reduction at all.

Soil drainage classes work well in some cases and not so well in others. Well-drained and moderately well-drained soils are not hydric and have generally high chromas and lack redoximorphic features in the surface horizon. Poorly drained soils are hydric and have generally low chromas throughout and have redoximorphic features in the surface horizon. The somewhat poorly drained soils, however, are not hydric by current criteria (U.S. Department of Agriculture Soil Conservation Service 1991), but have morphology and hydrology more like the hydric soils. For western Oregon, it would be better to delete the drainage class criterion and base the determination of hydric soils simply on morphology.

References

- Baldwin, E. M. (1981). *Geology of Oregon*. Kendall/Hunt Publishing Co., Dubuque, IA.
- Balster, C. A., and Parsons, R. B. (1968). "Geomorphology and soils of the Willamette Valley, Oregon," Spec. Rpt. 265, Oregon State Univ. Agr. Exp. Sta. and USDA Natural Resources Conservation Service.
- _____. (1969). "Late Pleistocene stratigraphy, southern Willamette valley, Oregon," *Northwest Sci.* 43, 116-129.
- Faulkner, S. P., Patrick, W. H., and Gambrell, R. P. (1989). "Field techniques for measuring wetland soil parameters," *Soil Sci. Soc. Amer. J.* 53, 883-890.
- U.S. Department of Agriculture Soil Conservation Service. (1991). *Hydric soils of the United States*. Miscellaneous Publication 1491.

9 Preliminary Investigations of Hydric Soil Hydrology and Morphology in Alaska¹

Introduction

Wet soils at five sites in the Matanuska-Susitna Valley in south-central Alaska have been monitored since the fall of 1991. In this paper, results are reported of the first 2 years of data collection, encompassing most of hydrologic years 1992 and 1993. Conclusions are necessarily tentative after only 2 years of monitoring.

The sites in the study form two drainage catenas and one independently located soil (Figure 1). The climate and geomorphic setting of the study area are described by Péwé (1975) and Clark and Kautz (In Publication). Briefly, the Bodenberg microlow and microhigh sites are on the Palmer Terrace in deposits of 0.5 to 1.5 m of Holocene loess over very cobbly glacial outwash. The isolated Disappoint site is located at the south end of the Matanuska Valley near the edge of a glacial till plain and mountain toe slope where 0.2 to 0.6 m of volcanic ash and loess have been deposited over glacial till. The SND and Histosol sites are in the southern Susitna Valley east of Palmer on a glacial outwash plain along the Little Susitna River; the SND soil is formed in Holocene loess and volcanic ash over glacial outwash, and the Histosol site is downslope in a deep black spruce (*Picea mariana*) bog. Site locations and soil taxonomy are presented in Table 1.

Precipitation is the main source of water at the Bodenberg sites. The seasonally perched water table is caused by receding frost in the spring and early summer; the microlow site also collects runoff in spring. In addition to meteoric inputs, the SND and Histosol sites also receive water from an unconfined aquifer in the outwash material (Glass 1983).

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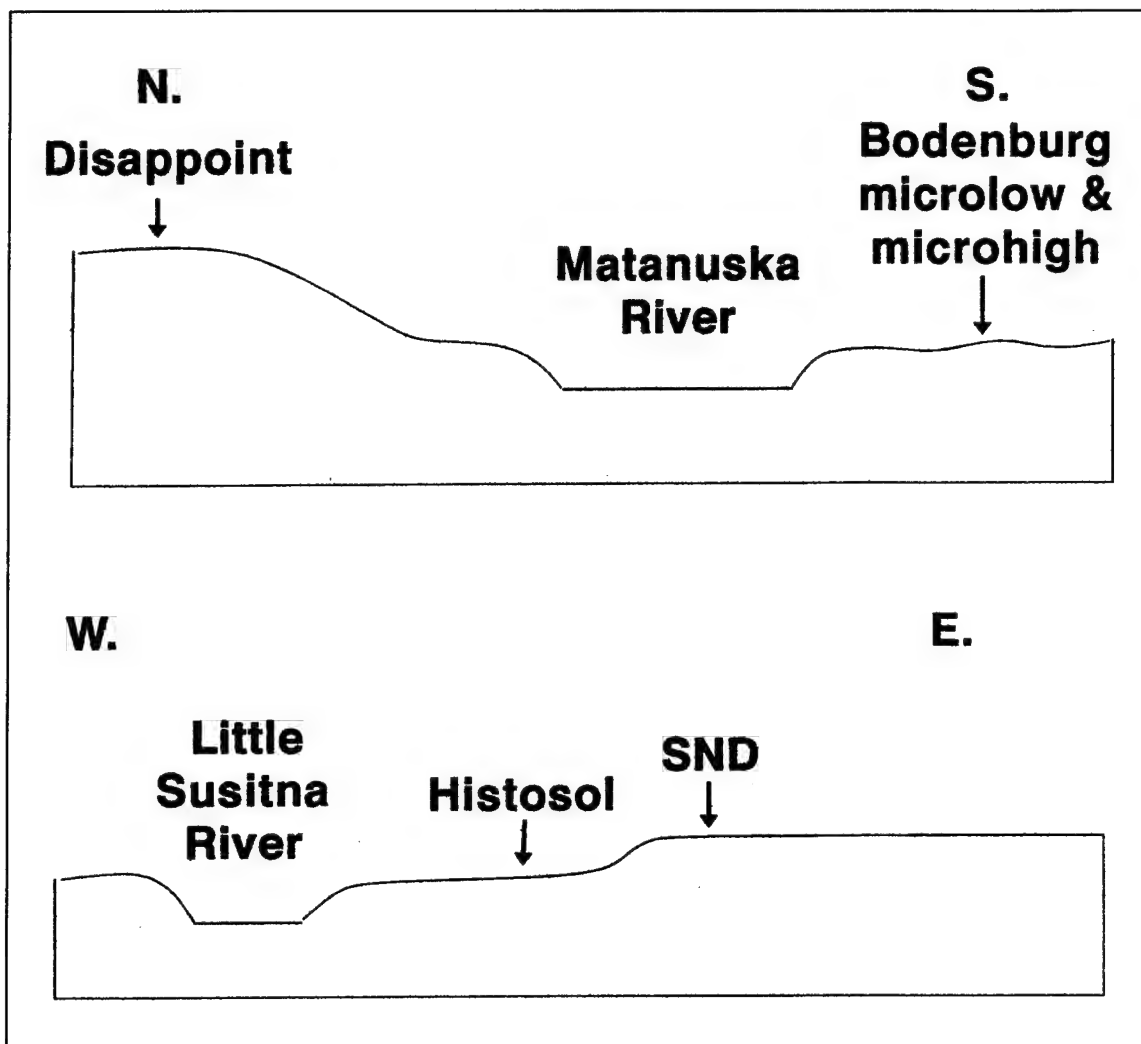


Figure 1. Relative positions of monitoring sites in Mat-Su Valley, southcentral Alaska

Table 1 Location and Taxonomy of Soils in the Matanuska-Susitna Valley		
Soil	Coordinates	Soil Classification
Bodenberg Microlow	61°34'46" N 149°04'26" W	Coarse-silty, mixed Typic Cryochrept
Bodenberg Microhigh	61°34'47" N 149°04'23" W	Coarse-silty, mixed Typic Cryochrept
Disappoint	61°37'17" N 149°02'38" W	Coarse-silty, mixed, nonacid Humic Cryaquept
SND	61°25'32" N 150°08'17" W	Coarse-silty, mixed, acid Typic Cryaquept
Histosol	61°25'35" N 150°08'22" W	Dysic Fluvaquentic Borosaprist

Data from nearby weather stations (Table 2) were used to characterize the climate of the monitoring sites—the Palmer AES weather station for the Bodenberg and Disappoint sites and the Wasilla 3S station for the SND and Histosol sites. The SND and Histosol sites are also near weather stations with short-term or incomplete records (the Lazy Mountain station has 11 years of record, and precipitation data at Point MacKenzie are available only for April through September).

Table 2
Climatic Data¹ Collected at Weather Stations Near the Study Sites

	Mean Annual Precipitation cm	Mean Summer ² Precipitation cm	Mean Annual Air Temperature °C	Mean January Air Temperature °C	Mean July Air Temperature °C	Frost-Free Days >0 °C	Snow Equivalent cm
Palmer AES	37.8	15.6	2.2	-10.0	14.4	127	
Wasilla 3S	40.9	17.4	2.8	-9.4	15.0	109	
Lazy Mt. ³	52.1	16.0	0.4	-6.8	13.3	107	28.7
Pt. MacKenzie	--	15.7	-1.1	-11.7	16.1	133	--

¹ Average based on historical records for 1970-1990 from the National Climatic Data Center Annual Summary, U.S. Department of Commerce.

² May through August.

³ 1992 data only.

Methods

Locations of the monitoring sites (Table 1) were determined by Global Positioning System. Air and soil temperatures were measured by thermocouple sensors and recorded by Omni data loggers, or taken manually (Table 3). Groundwater levels and hydraulic heads were determined with shallow piezometers. Soil moisture tension was measured in millibars with tensiometers (Soil Measurement Systems, Tucson, AZ). Redox potentials were measured with Jensen E2 platinum electrodes and a Model P5E oxygen/ORP meter (Jensen Instruments, Tacoma, WA). Instruments were monitored twice monthly from May 1 to September 15, and once a month the rest of the year due to frozen soils and deep snow cover.

Results and Discussion

Soil saturation and reduction

Tensiometer measurements indicated that neither Bodenberg soil was saturated within 50 cm of the surface during the growing season. Furthermore,

Table 3
Kinds and Depths of Instruments Installed at Wet Soil Monitoring Sites

Soil Name	Height of Air Temperature Measurements cm	Depth of Soil Temperature Measurements cm	Depth of Piezometers cm	Depth of Tensiometers cm	Depth of Redox Electrodes cm
Bodenberg Microlow	200	5, 10, 20, 50, 150 ¹	25a, 50a, 100a, 150a ² 25b, 50b, 100b, 150b	25a, 50a, 100a, 150a 25b, 50b, 100b, 150b	25, 50, 100, 150
Bodenberg Microhigh	--	5, 10, 20, 50, 150 ¹	25a, 50a, 100a, 150a 25b, 50b, 100b, 150b	25a, 50a, 100a, 150a 25b, 50b, 100b, 150b	25, 50, 100, 150
Disappoint	125	5, 10, 20, 50, 150 ¹	25a, 50a, 100a, 150a 25b, 50b, 100b, 150b 25c, 50c, 100c, 120c	25a, 50a, 100a, 150a 25b, 50b, 100b, 150b 25c, 46c, 83c, 120c ⁴	10, 25, 50
SND	125	5, 10, 20, 50, 100 ³	25a, 50a, 100a, 150a 25b, 50b, 100b, 150b	25a, 50a, 100a, 150a 25b, 50b, 100b, 150b	10, 25, 50
Histosol	50	1, 5, 10, 20, 50, 150 ³	100	100	--

¹ Temperatures measured by thermocouple sensor and recorded by Omni data logger.

² a, b, and c indicate replicates, and data presented in corresponding figures are average values unless otherwise specified.

³ Measured manually biweekly.

⁴ Nonstandard depth due to presence of gravel.

no water was recorded in piezometers in either soil during the first 2 years of the study. Iron stability diagrams of Eh and pH indicate a threshold redox potential for iron reduction of $E_h = 341$ mV for Bodenberg low and 300 mV for Bodenberg high soils. Using this value, iron reduction likely occurred a few days in early September 1992 and mid-July 1993 in the Bodenberg low soil, and about a week during late May 1993 in the Bodenberg high soil. Such reduction was not related to saturation as indicated by tensiometer measurements.

There were two annual periods of saturation observed in the Disappoint soil. Based on piezometer readings (Figure 2), the soil was saturated within 25 cm of the surface in the spring (from 20 April to 2 June 1992, and from 10 April to 20 May 1993) and again in the fall (from 12 October to 30 November 1992, and from 17 September to 24 November 1993). The soil saturation period within 50 cm was even longer. Soil moisture tension measurements agreed with the piezometers (Figure 3). Iron reduction in the Disappoint soil (threshold E_h of 270 mV) occurred at 25 cm between 10 October and 22 November, 2 June and 8 July 1992, and 21 May and 17 June 1993 (Figure 4). In 1992, the reduction occurred nearly 3 weeks after the saturation and extended over a month after the water table dropped below 25 cm. Such delayed reduction was not observed in the spring of 1993, but extended reduction was observed.

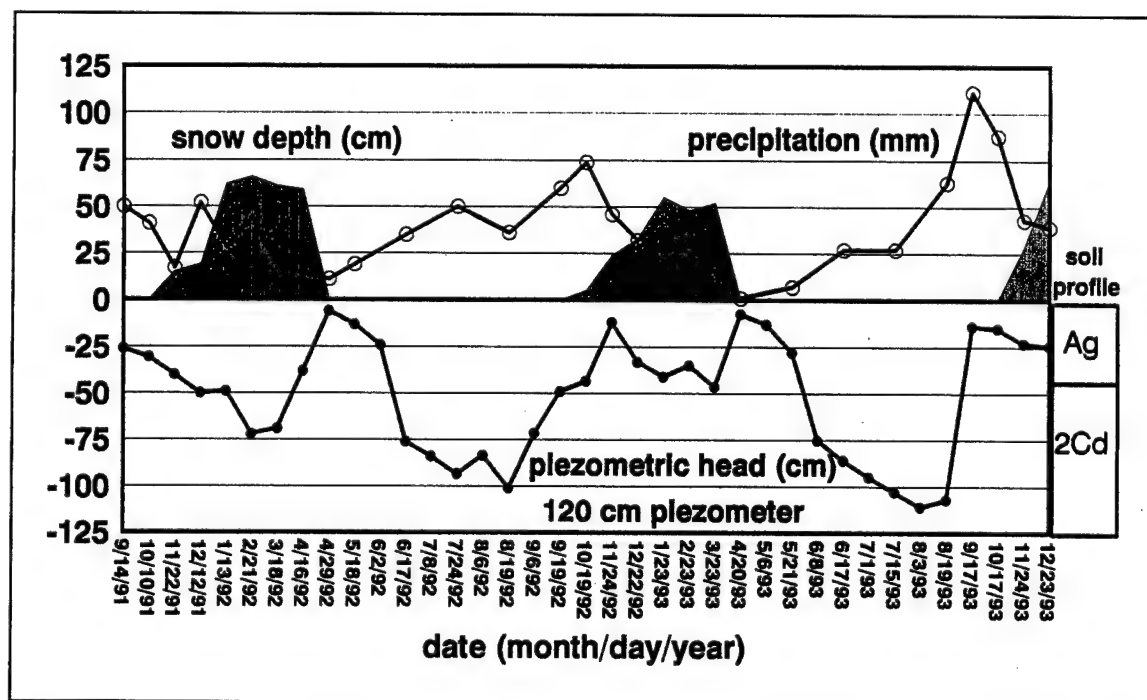


Figure 2. Piezometric head (bottom) as measured with a piezometer at 120-cm depth and snow depth and precipitation (top) at Disappoint site

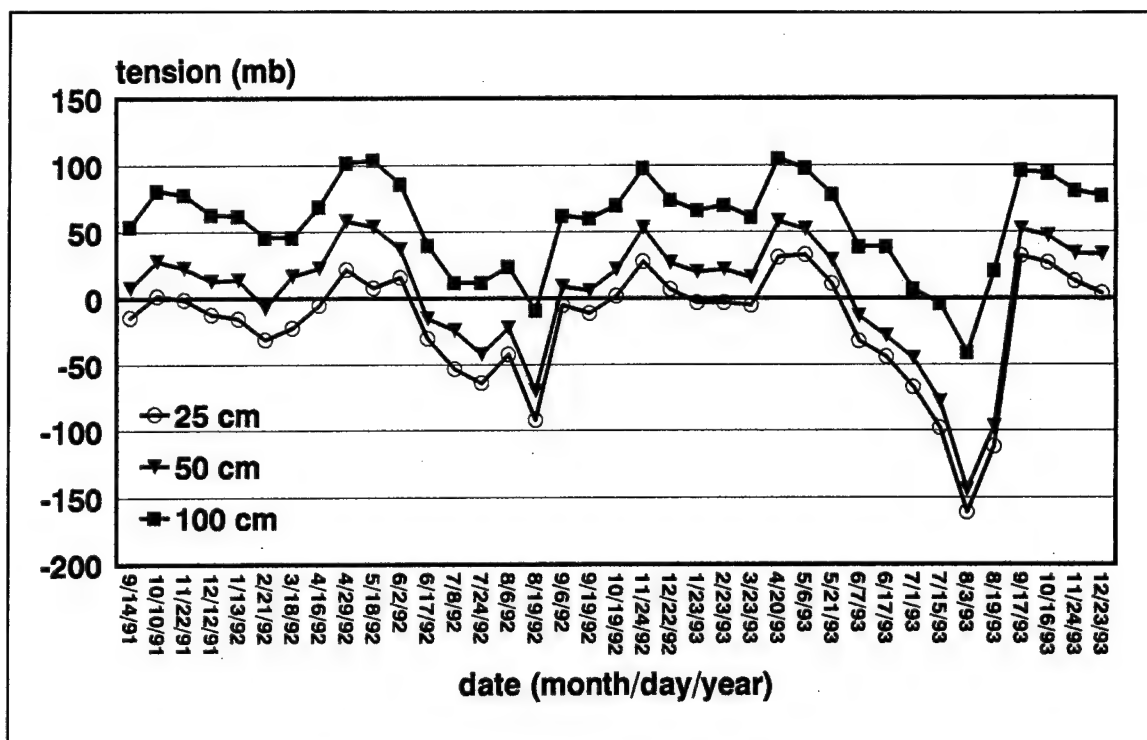


Figure 3. Soil moisture tension as measured with tensiometers at depths of 25, 50, and 100 cm at Disappoint site

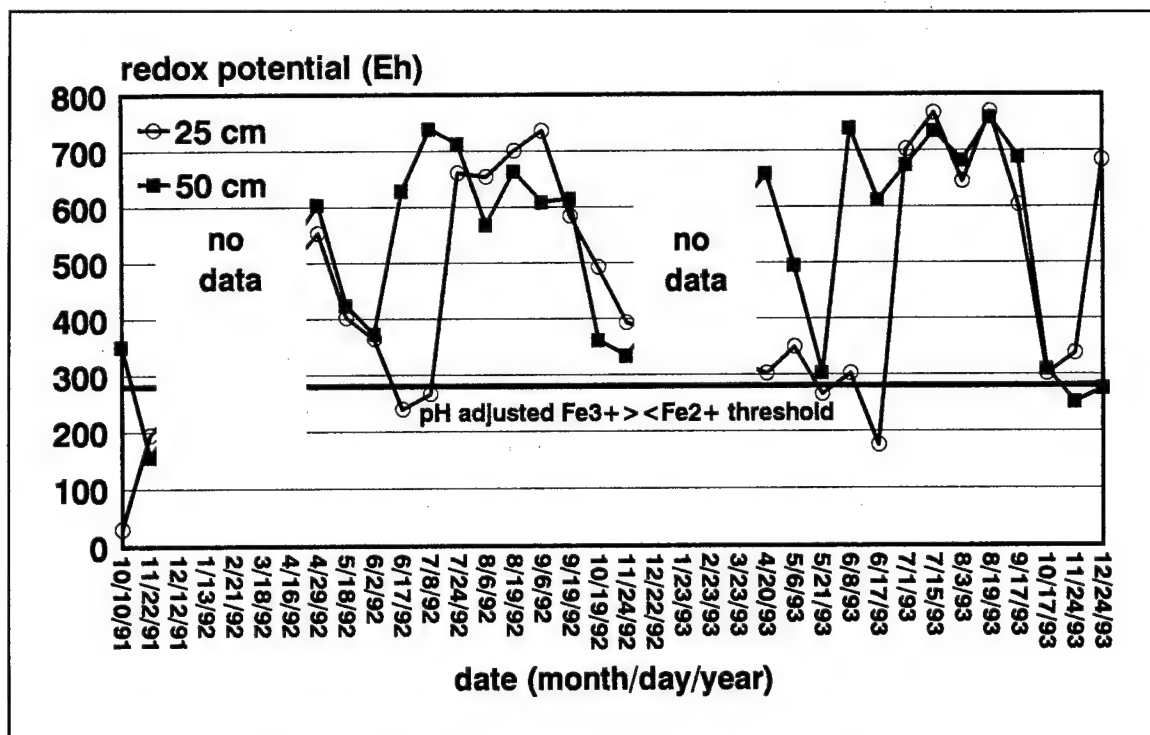


Figure 4. Redox potentials as measured with platinum probes at depths of 25 and 50 cm at Disappoint site

One reason for the delay in reduction in the spring may be that surface runoff was oxygenated; by midsummer, soil water may have become anaerobic as the water flow decreased. The capillary fringe and the abundant supply of organic matter would contribute to the extended period of reduction after the water table dropped. Iron-reducing conditions occurred at 50 cm only briefly in the spring. This may be due to the limited supply of organic carbon (< 1 percent) in the compacted glacial till of the 2Cd horizon. Seasonal frost was not present (Figure 5), presumably because deep snow cover protected the soil from freezing.

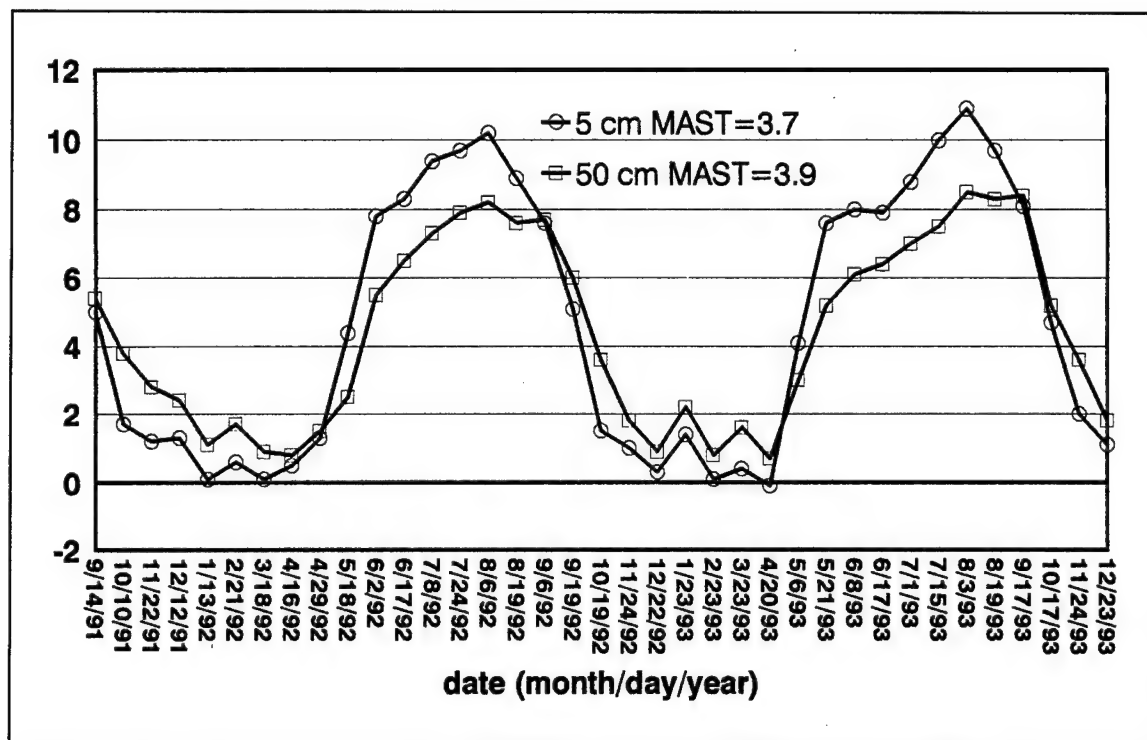


Figure 5. Soil temperatures as measured with thermocouples at depths of 5 and 50 cm at Disappoint site (MAST denotes mean annual soil temperature)

Piezometer and snowfall measurements indicate that high snowfall in 1992 caused the SND soil to be saturated above 50 cm in the spring longer in 1992 than in 1993 (29 April to 9 June 1992 versus 1 to 7 May 1993). A warmer and drier summer in 1992 caused the late summer rise in water tables to be less pronounced in 1992 than in 1993.

The threshold Eh value for iron reduction in the SND soil was 300 mV. Reduction occurred only in the fall of 1991, 1992, and 1993, which was outside of the growing season. The reduction at 25 cm in 1992 was likely caused by the capillary fringe, since the water table was at 50 cm. The lack of reduction in the spring may have been due to high oxygen contents of the recharging surface waters. This may also explain the month-long delay of reduction after saturation at 50 cm in the fall of 1993.

Snow depth, piezometric head, and soil temperatures were recorded in the Histosol, but not redox potentials. Again, the water table was controlled by snowfall and late summer rainfall. The water table was within 50 cm of the surface 90 percent of the time.

Thickness of reduced zone above water table

There was no water table detected at either Bodenberg site. The brief periods of reduction at 25 cm in the Bodenberg high soil during spring may have been due to soil saturation above the receding seasonal frost. In the Disappoint and SND soils, the thickness of the reduced zone above the water table was generally less than 50 cm.

Evidence of oxyaquic conditions

Free water was never recorded at any depth in either Bodenburg soil, so neither aquic nor oxyaquic conditions were observed. In the late spring in the Disappoint and SND soils, oxyaquic conditions were caused by surface-fed sources of runoff and groundwater.

Effects of soil temperature

The brief episode of reduction in the Bodenberg high soil occurred from April 15 to May 15, which was right before the beginning of the growing season. Thus, reduction was more related to soil water content than to soil temperature. In the Disappoint soil, too, reduction seemed more affected by soil water content than by soil temperature. In the spring, soil reduction occurred when temperatures at 5 cm rose above 3 °C and the soil was saturated (Figures 4 and 5); in the fall, reduction occurred after August 31 when soil temperatures dropped rapidly from 8 °C to below 2 °C. In the SND soil, reduction occurred in the fall of 1993 after water tables had risen above 50 cm and soil temperature had dropped below 5 °C. It is apparent that the reduction at this site, too, was more related to soil water content than to soil temperature.

Indicators of actual growing season

All soils studied had mean annual soil temperatures at 50 cm greater than 0 °C but less than 8 °C, and the difference between mean summer soil temperature and mean winter soil temperature was less than 15 °C. Therefore, all soils were assigned to the cryic soil temperature regime (Ping 1987). The Natural Resources Conservation Service (formerly Soil Conservation Service) defined the growing season for wetland delineation purposes as that time of the year when the soil temperature was above biologic zero, or above 5 °C (Soil Conservation Service 1991). It further recommended that soils with

cryic soil temperature regimes be assigned growing seasons extending from June 1 to August 31 if actual soil temperature data were unavailable. Data show, however, that most of the reduction occurred either before June 1 or after August 31, when soil temperatures at 5 cm were mostly below 5 °C. Thus, growing season dates estimated for cryic soil temperature regimes did not adequately predict the actual period of soil reduction.

The length of growing season periods estimated from 28 °F and 32 °F air temperature thresholds for the average year reported in local soil survey reports are given in Table 4. These were much longer than the 92 days recommended for the cryic regime. Soil temperatures on the sites for this study rose above 5 °C from mid- to late May and dropped below 5 °C in the autumn in mid- to late September.

Table 4		
Growing Season of the Monitored Soils¹		
Sites	Growing Season (days) Based on	
	28 °F Air Temperatures	32 °F Air Temperatures
Bodenberg Microlow and Microhigh	148	127
Disappoint	115	108
SND and Histosol	140	133
¹ From 1993 U.S. Department of Agriculture Alaska Agricultural Statistics and the 1992 National Climatic Data Center Climatological Data Annual Summary.		

Meeting criteria and definition of hydric soils

The Bodenberg soils are classified in an Aquic subgroup but are moderately well drained and are not frequently ponded or flooded for 1 week or more during the growing season. In fact, free water was never recorded in the piezometers during this 2-year reporting period. Therefore, the Bodenberg soils did not meet the criteria for hydric soils. Each soil was reduced at 25 cm for one reading during the study, but these short episodes of reduction did not coincide with low moisture tension. Therefore, the requirements of the definition of hydric soils were not met.

The Disappoint soil is classified in an Aquic suborder and is poorly drained because it has a frequently occurring water table at less than 0.5 ft from the surface more than 2 weeks either in early or late summer. The Disappoint soil was reduced for several weeks in both 1992 and 1993. This soil meets both the criteria and definition for hydric soils.

The SND soil is classified in the Aquic suborder and is somewhat poorly drained. However, it does not have a water table at less than 0.5 ft from the

surface for more than 2 weeks during the growing season. Therefore, it does not meet the criteria for hydric soils. The SND soil was reduced once during the summer of 1992 in association with a high water table and low moisture tension, but was not reduced during or immediately after the spring high water table. This short data record indicates that SND probably does not meet the definition of hydric soils either.

The Histosol is classified as a Cryohemist, not a Folist; therefore, it meets the criteria for hydric soils. Redox measurements were not taken in the Histosol, so it cannot be proved that it is anaerobic and therefore meets the definition of hydric soils.

Both Bodenbergs soils have morphological features listed as hydric soil field indicators in the "Corps of Engineers Wetlands Delineation Manual" (Environmental Laboratory 1987). These features include iron masses in gray matrixes below the dark surface horizon, which indicate part of the soil profile is reduced and part is oxidized. However, soil morphology or hydrology alone cannot be used to identify these hydric soils because of relict mottles or oxyaquic conditions. A portable redox meter would help the field soil scientist to correctly identify hydric soils.

Preliminary Conclusions

In most cases, redoximorphic features can be used to indicate soil wetness and water movement. However, such features alone cannot be used to determine the hydric status of soils such as the Bodenbergs soils (Clark and Ping 1993).

Redox fluctuations for the SND and Disappoint soils suggest that significant biological activity occurs outside of the June 1 to August 31 growing season dates assigned for soils with cryic soil temperature regimes. It is common in subarctic and boreal climates that high water tables occur in late spring due to thawing and snowmelt and in late summer or early fall due to rain. Actual growing season dates indicated by redox potential measurements extend to late spring (April) and late fall (November). Phenological studies also support a vernal rather than summer onset of the growing season (Mitchell 1980). Therefore, the definition of growing season in the cryic soil temperature regime should be revised—from April 15 to November 1, or when soil temperature in the rooting zone (0 to 25 cm) is above 0 °C.

Microbial activity as indicated by decreased redox potentials is more closely related to soil water conditions than to soil temperature. Most data suggest a particular duration of saturation required before soils become reduced. The duration depends on the sources of groundwater. If the source is oxygenated, as in the example of Disappoint and SND soils in the spring, there is a 2-week or longer lag before reduction occurs.

Significant reduction occurred above the free water table at various heights. In the Disappoint soils, reduction occurred at 25 cm between 18 May and 8 July 1992 and between 20 April and 17 June 1993 despite the water table dropping from approximately 10 to 80 cm. This suggests that reducing conditions persist after the free water table drops below the depth of reduction. In the SND soil, reduction was measured at both 25 and 50 cm, yet the water table was only at 50 cm. Therefore, there was more than 25 cm of reduced zone above the water table. It is evident that redoximorphic features alone, especially mottles, cannot be used to identify reducing conditions unless a gleyed horizon is present where most of the matrix has chromas less than 2, such as in the Bg horizon of the Disappoint soil.

References

- Clark, M. H., and Kautz, D. "Soil survey of Matanuska-Susitna Valley area, Alaska," In Preparation, USDA Natural Resources Conservation Service, Washington, DC.
- Clark, M. H., and Ping, C. L. (1993). "Morphology and hydrology of five seasonally wet soils in southcentral Alaska." *Agronomy abstracts*. American Society of Agronomy, Madison, WI.
- Environmental Laboratory. (1987). "Corps of Engineers wetlands delineation manual," Technical Report Y-87-1, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.
- Glass, R. L. (1983). "Hydrological data for Point MacKenzie Area, Southcentral Alaska," Open File Report 83-143, U.S. Geological Survey, Anchorage, AK.
- Mitchell, W. W. (1980). "Using phenology to characterize spring seasons in Alaska," *Agroborealis* 12, 42-45.
- Péwé, T. L. (1975). "Quaternary geology of Alaska," Geological Survey Professional Paper 835, U.S. Department of Interior, Washington, DC.
- Ping, C. L. (1987). "Soil temperature profiles of two Alaska soils," *Soil Sci. Soc. Am. J.* 51, 1010-1018.
- U.S. Department of Agriculture Soil Conservation Service. (1991). *Hydric soils of the United States*. 3rd ed., U.S. Department of Agriculture, Miscellaneous Publication No. 1491, Washington, DC.

10 Synthesis¹

The studies described in this report were conducted with similar research designs and methodologies in very different geomorphic regions. Preliminary results indicate some common problems in applying the definition, criteria, and indicators of hydric soils in the research arena. This in turn raises questions about the usefulness of protocols to identify hydric soils in the regulatory arena as well. The research addressed the following general questions relevant to hydric soils:

- a. What are the relationships among saturation, anaerobiosis, and reduction in the soils that were monitored?
- b. How does soil temperature affect anaerobiosis and reduction in these soils?
- c. What morphological features might be useful in identifying soils that meet hydric soil criteria?

To address these questions, researchers raised many other issues that have long been central to the hydric soils debate. For example: Is it part of the hydric soil concept that hydric soils be reduced with respect to iron or simply lacking in oxygen? What proportion of the soil matrix should be anaerobic/reduced? What is the extent of the capillary fringe and what is its role as a reduced zone? Is the growing season relevant to identification of hydric soils? If so, how should it be defined? How does one distinguish relict from contemporary hydric soil features?

These preliminary reports do not provide definitive answers. However, most of the projects reported here will continue for at least several more years, adding greatly to the understanding of soil/water interactions and to the evolving concept of what constitutes and distinguishes a wetland soil.

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In this synthesis, an attempt is made to address some of the questions presented above based on information given in the preceding chapters. Readers should examine the individual chapters for details of results and the researchers' conclusions. The individual investigators may not agree with all that is said in this synthesis, and any errors in interpretation of their results are those of these authors.

Anaerobic Conditions

The definition of hydric soil requires that the soil be anaerobic in the upper part. "Anaerobic" in turn is defined as lacking in free molecular oxygen (O_2) (U.S. Department of Agriculture (USDA) Soil Conservation Service 1991). This is significant to the delineation of hydric soils because most morphological indicators are based on reduction of iron rather than mere absence of oxygen. Some wetland scientists and delineators interpret the definition to mean that a soil has only to be reducing with respect to nitrate (next after oxygen in the redox sequence) in order to be hydric, and this concept dovetails nicely with the recognition of denitrification as an important water quality function of wetlands. Others interpret the definition as requiring reduction of iron, partly because a convenient field indicator is available. Few of the studies included in this report measured oxygen content of the soil to determine anaerobiosis directly, partly because of the technical difficulties involved in such measurements.

Platinum electrode readings in nonhydric, somewhat poorly drained soils in the Oregon study indicated seasonal depletion of oxygen but not reduction of iron. Iron reduction occurred in one of the poorly drained Dayton soils, but only for short periods each year. In contrast, other soils, such as the Delmar and Washtenaw soils in the Indiana study, exhibited near-surface redox potentials that were low enough for iron reduction for several months in the spring and summer.

Oxygen contents of the soil solution stayed as high as 6 percent in somewhat poorly drained soils in Texas and yet allowed microsite reduction of iron. This raises the question of how to interpret the hydric soil definition: how much of the soil matrix must become anaerobic or reduced in order for the soil to be considered hydric?

Capillary Fringe

The criteria for hydric soils require different threshold water table depths depending, in part, upon soil texture and permeability. Water tables must be within 15 cm of the surface for sands, 30 cm for other highly permeable soils (>6 in./h), and 45 cm for slowly permeable soils (<6 in./h) (USDA Soil Conservation Service 1991; these criteria were recently restated as 0, 15, and 30 cm without changing the list of hydric soils (Federal Register 60:10349,

1995)). These graduated water table thresholds are based on three assumptions: (a) that there is a significant capillary fringe above shallow water tables, (b) that the height of the fringe varies with soil texture, and (c) that anaerobic conditions can develop within the capillary fringe.

Tensiometer data indicated that matric potentials can be positive or only very slightly negative at heights of 15 to 50 cm above measured water tables (Table 1). Soils in Texas had matric potentials of < 1 cbar at the 25-cm depth in fine and fine-loamy materials for 10 to 60 days longer than they had free water tables at or above that depth. Similarly, silt-loam surface and subsurface horizons in Louisiana had positive matric potentials at the 25-depth for 10 to 60 days longer than they had free water tables.

Table 1 Thickness of the Capillary Fringe Inferred From Reported Data		
Thickness, cm	Texture of Affected Horizon	Study Site
40	Clay	LA
20-50	Silt loam	LA
40-50	Silt loam	LA
15	Fine sandy loam; organic; unspecified	MN
30-40	Sandy	ND

Anaerobic or reducing conditions were found above the water table in the Alaska and Louisiana studies, but primarily in microsites. There was some concern among several researchers that the data collection period and methodology were not refined enough to isolate reduction of iron above water tables, much less to distinguish between anaerobic and aerobic conditions within the capillary fringe.

Duration of Saturation Needed to Produce Anaerobic Conditions

Hydric soils Criterion 2 (USDA Soil Conservation Service 1991, see Chapter 1 of this report) specifies water table depths and durations and was designed to extract appropriate soil series from the national soils database according to information in soil interpretation records. This criterion states that soils must have high water tables for at least 2 consecutive weeks during the growing season. The criterion was never intended to be used to identify hydric soils in the field (Mausbach 1994); nonetheless, the 2-week guideline has been the basis for many wetland delineations and much controversy. The studies described in this report monitored water tables and Eh too infrequently to determine definitely the number of days required for anaerobic conditions

or iron reduction to occur after onset of saturation, but the data can be used to decide whether the 2-week guideline is reasonable.

There was considerable variation among studies in duration of saturation necessary to cause anaerobiosis and/or reduction. Ferrous iron appeared within 7-14 days after saturation in some Texas soils, and oxidized rhizospheres became apparent in one soil after 4-8 weeks. Both the China and Cieno soils of the Texas coastal plain were saturated on 53 percent of sampling dates; however, the China soil experienced microsite reduction only 7 percent of the time, whereas the Cieno soil was reduced 33 percent of the study. Soils of the Mississippi River embayment in Louisiana became reduced almost immediately after heavy rains. In an Oregon soil, there was a lag of about 1 month between saturation and anaerobiosis, with an additional 2- to 3-month lag before iron reduction occurred. Several studies reported delays between saturation and reduction that were considerably longer than 14 days.

Many factors probably affected the length of time a soil was saturated before becoming reduced, including soil temperature, organic content, and microbial activity. The Louisiana study reported that reduction proceeded more slowly in the spring as water tables rose than in the summer after heavy rains. The Oregon study noted that duration of saturation before reduction varied with depth, deeper horizons having longer time lags than shallower horizons. Infrequency of measurement prevented more precise determinations of time lags between onset of saturation, anaerobiosis, and reduction in these studies. Nonetheless, it is clear that time lags vary considerably among soils and are affected by a variety of environmental conditions. It is probably safe to say that the National Technical Committee for Hydric Soils (Mausbach 1994) was justified in recommending that Criterion 2 for hydric soils, which requires at least 14 days of high water tables during the growing season, should not be applied to field situations but should be reserved solely for sorting soils records within the Natural Resources Conservation Service (NRCS) computerized database.

The Indiana report raises an important caution that iron stability diagrams may not accurately reflect actual iron species in the soil. The authors report positive tests for ferrous iron at times when Eh readings predicted negative tests. The New Hampshire report also urged caution in interpreting platinum electrode data because of great variability within and between soils and the difficulty in explaining such variability in terms of measured hydrology. They conclude that redox data probably should be used to characterize long-term trends rather than to infer iron reduction at specific times in specific horizons.

Growing Season

The definition and criteria for hydric soils follow *Soil Taxonomy* (Soil Survey Staff 1975, 1994) in the premise that soil oxygen supplies are depleted by microorganisms. Consequently, it has been assumed that soil saturation

does not lead to chemical reduction unless the soil microbial community is active. *Soil Taxonomy* uses 5 °C as a threshold soil temperature below which soil microbial metabolism is assumed to be negligible. *Hydric Soils of the United States* (USDA Soil Conservation Service 1991) defines the growing season as the period of the year when soil temperatures in the upper part are above biological zero (i.e., 5 °C). Alternative methods to estimate growing season dates are described in Chapter 1 of this report.

The concept of the growing season based on 5 °C thresholds was not very useful to the reported studies. Most of the soils in Texas were above 5 °C all year long. At the other extreme of temperatures, the Alaska study found significant iron reduction occurring at temperatures as low as 2 and 3 °C, and the Minnesota study found reduced conditions when soil temperatures were below 3 °C. In Oregon, there was better correspondence between iron reduction and soil temperatures of 8 °C than 5 °C, but the investigators concluded that reduction was controlled by soil saturation rather than by temperatures.

Hydric Soils of the United States provided guidelines for estimating growing season dates from soil temperature regimes. Those studies that addressed the question found the guidelines to be wrong, but neither did they endorse current guidance to estimate growing season from 28 °F air temperature thresholds, usually because soil temperatures lag behind air temperatures in the autumn. Soil temperatures were also controlled by snow cover in the colder parts of the nation. Table 2 compares approximate growing season dates at the monitoring sites based on temperature regime regions, average dates of 28 °F air temperatures, and soil temperatures measured in these studies.

Morphology of Hydric Soils: Testing Proposed Regional Hydric Soil Indicators

The NRCS was developing lists of regional indicators of hydric soils while the chapters of this report were being written. Some of the authors evaluated specific NRCS proposals. Such evaluations have to be tentative because duration of record was so short for most of these studies.

The Minnesota and Louisiana studies both found hydric soils that had the morphology described by the depleted matrix indicator (regional indicators FM3 and F3, respectively) (USDA Soil Conservation Service 1994):

directly beneath an ochric or umbric epipedon having chroma 2 or less and thickness 30 cm or less, 60 percent or more of the matrix is depleted of iron in all layers to a depth of 35 cm or more and has ...
(b) value 5 or more and chroma 2 or less and has distinct or prominent redox concentrations as iron masses...

Table 2
Growing Seasons for the Monitoring Sites Based on Different Definitions and Data Sources

State	County	Soil Temperature Regime		> 28 °F (– 2 °C) Air Temperatures, 5 Years in 10 ²	Soil Temperature in the Upper Part ³	
		Regime	Assumed Growing Season ¹		> 5 °C (41 °F)	> 8 °C (46 °F)
AK	Mat-Su Area (Bodenburg)	Cryic	Jun-Aug	1 May-23 Sep	20 May-20 Sep	
	Mat-Su Area (Disappoint)	Cryic	Jun-Aug	1 May-23 Sep	20 May-20 Sep (1992) ⁴ 10 May-15 Oct (1993) ⁴ 1 Jun-5 Sep (1992) ⁵ 20 May-30 Oct (1993) ⁵	2 Jun-1 Sep (1992) ⁴ 8 Jun-7 Sep (1993) ⁴ 30 Jul-10 Aug (1992) ⁵ 20 Jul-15 Sep (1993) ⁵
	Mat-Su Area (SND/Hist)	Cryic	Jun-Aug	6 May-20 Sep		
IN	Jennings	Mesic	Mar-Oct	11 Apr-25 Oct	15 Mar-15 Jan	1 Apr-20 Nov
	Parke	Mesic	Mar-Oct	6 Apr-2 Nov	1 Mar-10 Dec	15 Mar-15 Nov
LA	Acadia	Hyperthermic	Feb-Dec	7 Feb-10 Dec		
	Beauregard	Hyperthermic	Feb-Dec	21 Feb-1 Dec		
	Calcasieu	Hyperthermic	Feb-Dec	26 Jan-29 Dec		
	Iberville	Hyperthermic	Feb-Dec	26 Jan-16 Dec		
	Livingston	Hyperthermic	Feb-Dec	23 Feb-26 Nov		
	Rapides	Thermic	Feb-Oct	21 Feb-26 Nov		
	St. Landry	Hyperthermic	Feb-Dec	8 Feb-1 Dec		
	W. Baton Rouge	Hyperthermic	Feb-Dec	17 Feb-6 Dec		

(Continued)

¹ USDA Soil Conservation Service (1991).

² Data provided in county soil survey reports or by the USDA NRCS Climatic Data Access Facility, Portland, OR, for the county seat or weather station closest to the monitoring site.

³ Based on measurements made at 25-cm depth, except where noted.

⁴ Measured at 5-cm depth.

⁵ Measured at 50-cm depth.

Table 2 (Concluded)							
State	County	Soil Temperature Regime		> 28 °F (- 2 °C) Air Temperatures, 5 Years in 10 ²	Soil Temperature in the Upper Part ³		
		Regime	Assumed Growing Season ¹		> 5 °C (41 °F)	> 8 °C (46 °F)	
MN	Otter Tail	Mesic	Mar-Oct	25 Apr-7 Oct	1 May-15 Oct	5 May-15 Oct	
	Pennington	Frigid	May-Sep	8 May-1 Oct	25 Apr-20 Oct (1992) 25 Apr-20 Oct (1993)	10 May-25 Sep (1992) 5 May-30 Sep (1993)	
	Rice	Mesic	Mar-Oct	28 Apr-13 Oct	1 May-1 Nov	5 May-15 Oct	
NH	Coos	Frigid	May-Sep	17 Jul-23 Sep			
	Hillsborough	Mesic	Mar-Oct	5 May-5 Oct			
	Cavalier	Frigid	May-Sep	15 May-22 Sep	5 May-20 Oct	10 May-1 Oct	
ND	Divide	Frigid	May-Sep	7 May-27 Sep			
	Ransom	Frigid	May-Sep	10 May-27 Sep			
	Benton	Mesic	Mar-Oct	5 Mar-20 Nov	15 Jan-25 Dec	20 Feb-5 Dec	
TX	Polk	Mesic	Mar-Oct	3 Apr-6 Nov	25 Jan-25 Dec	20 Feb-22 Nov	
	Jefferson	Hyperthermic	Feb-Dec	5 Feb-23 Dec			
	Victoria	Hyperthermic	Feb-Dec	3 Feb-28 Dec			

This indicator would separate hydric and nonhydric phases of Commerce soil in Louisiana and separate Kratka hydric soils from nonhydric Smiley soils in Minnesota.

The Minnesota study also found thin layers of muck in untilled hydric soils, which would satisfy indicator FMs:

presence of muck either on the surface or in the mineral surface layer having a combined thickness of 10 cm or more.

Proposed indicator MM5 separated hydric and nonhydric phases of Nerstrand soil in Minnesota, too. MM5 is

presence of distinct or prominent redox concentrations on ped faces or ped interiors in a zone more than 10 cm thick in the upper 30 cm of the mineral soil and has matrix value of 3 or less and chroma 1 or less and redox concentrations as masses with value 4 or more and chroma 4 or more.

The New Hampshire study specifically assessed the usefulness of six proposed hydric soil indicators, including accumulations of muck and several of the indicators specific to sandy soils. Both hydric and nonhydric soils had muck layers thick enough to meet the proposed hydric soil indicators (≥ 3 cm). E-horizon color patterns seemed a promising indicator, but the specific color criteria needed revision for the New Hampshire soils. The Minnesota study found that the draft indicator list did not include any indicators that captured the wettest Mollisols in their Faribault and Dalton transects.

Morphology of Hydric Soils: Problem Soils

The "Corps of Engineers Wetlands Delineation Manual" (hereafter the 1987 Manual; Environmental Laboratory 1987) recognized certain problem soils for which its list of indicators did not work, including soils from red parent materials or with thick, dark A horizons. The Minnesota and North Dakota studies included soils with A horizons that were deeper than the 10-in. depth recommended for inspection of low chroma colors by the 1987 Manual. The Louisiana study included soils in Red River Valley alluvium and sodium-affected soil. Sandy soils were described in the New Hampshire study.

Results of the Minnesota, North Dakota, and Oregon studies suggest considerable difficulty in articulating useful indicators for hydric Mollisols, especially from such short duration data sets. The most reliable indicators in Minnesota and North Dakota seemed to be presence of organic horizons in the wettest locations. More useful in locating the hydric/nonhydric boundary in all three studies were iron concentrations in depleted matrixes in the B or E horizons below the mollic epipedon. Iron masses, including oxidized rhizospheres, were found high in the mollic epipedon more frequently in

Oregon than in Minnesota and North Dakota. The authors recommended examination of soil profile features across the entire drainage catena, with particular attention to localized depressions and water flow paths. Redoximorphic features seemed to be more common and easier to interpret in the Oregon Mollisols than in those of the northern Great Plains.

The Louisiana study tested two indicators developed for other Land Resource Regions (LRRs) that may have been applicable to similar soils in the study area, which was within LRRs T and O, but found that they did not transfer. A natric soil testing indicator for LRR D did not work in the high sodium soils in LRR T, and a red parent material indicator did not work in the heavily tilled soils of the Red River Valley in LRR O. The authors concluded that reliable hydromorphic indicators are still lacking for soils derived from red parent materials in Louisiana, with respect to both hydric soils and *Soil Taxonomy*.

Morphology of Hydric Soils: Relict features

The Texas and Alaska studies in particular noted extensive occurrence of hydric soil morphology that did not seem to correspond to contemporary redox records. In Texas it was suspected that extensive cultivation had altered surficial hydrology enough that soil morphology was no longer indicative of current hydrology and flow paths. The Alaska landscapes were dynamic enough that water regimes were changing more rapidly than soil morphology. High organic matter contents of Alaskan soils added further opportunities for periodic microsite reduction without whole-horizon saturation.

Alternative Proposals to Interpret Hydromorphic Features

The authors of the Indiana report used color indices to predict duration of saturation. The indices were calculated by averaging Munsell chroma (or chroma and hue) weighted by percent volume in a particular horizon. Regression against duration of saturation indicated that such indices predict 60 to 80 percent of the variability in soil water table durations. Application of such indices in the field would require more thorough soil characterization than is normally performed in wetland delineations.

The New Hampshire report noted a correspondence between depth of ortstein in Spodosols and the 50-percent frequency depth of the water table. The Minnesota report recommended that investigators carefully examine changes in hydromorphic features across the drainage catena in Mollisol landscapes. For instance, mollic epipedons generally were darker and thicker and contained more organic carbon as one progressed downslope into closed depressions. Subsoil horizons also were grayer and iron masses were more pronounced and shallower. Presumably, one would draw hydric soil

boundaries by judging where on the transect such combinations of redoximorphic features become strongly enough developed.

The authors of the Alaska report recommended carrying a portable Eh meter to help determine whether hydric soil indicators were relict or contemporary. The α, α' -dipyridyl test is also a useful and less expensive indicator of iron reduction. Wetland delineators have traditionally been hesitant to use a negative result in the ferrous iron test as a negative indicator of hydric soils because of the potential that iron reduction may occur at some time of the year other than when the site was visited. On the other hand, the results of the Texas study also raise the need for alternative tests of contemporary reduction regimes.

References

- Environmental Laboratory. (1987). "Corps of Engineers wetlands delineation manual," Technical Report Y-87-1, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.
- Mausbach, M. J. (1994). "Classification of wetland soils for wetland identification," *Soil Survey Horizons* 35, 17-25.
- Soil Survey Staff. (1975). *Soil taxonomy*. Agriculture Handbook 436, U.S. Department of Agriculture, Washington, DC.
- _____. (1994). *Keys to soil taxonomy*. 6th ed., USDA Soil Conservation Service, Washington, DC.
- U.S. Department of Agriculture Soil Conservation Service. (1991). *Hydric soils of the United States*. Misc. Pub. 1491. Washington, DC.
- _____. (1994). "Field indicators of saturated hydric soils in the United States, Testing Version February 1, 1994," Washington, DC.

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13. ABSTRACT (Maximum 200 words) This report presents preliminary results from the Wet Soils Monitoring Project, a cooperative research project supported jointly by the U.S. Department of Agriculture Natural Resources Conservation Service (NRCS) and the U.S. Army Engineer Waterways Experiment Station. The work is being performed under the direction of the NRCS by investigators at land-grant universities in eight states: Alaska, Indiana, Louisiana, Minnesota, New Hampshire, North Dakota, Oregon, and Texas. Investigators are using similar instruments and research designs at each site to monitor depth, duration, and frequency of soil saturation, soil temperatures, and oxidation/reduction status at various depths in soils representing a gradient from drier to wetter conditions. Preliminary results are based on 2 years of monitoring at most sites. Investigators reported time lags between soil saturation and reduction of iron ranging from several days to several weeks, depending upon temperature and other factors. Some soils were anaerobic for long periods without exhibiting iron reduction. Growing seasons based on measured soil temperatures often differed considerably from those based on soil temperature regime regions or on >28 °F air temperatures. Longer monitoring periods are required to identify reliable morphological indicators of hydric soil hydrology.				
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